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(54) Title: CHIRAL PHOSPHINES, TRANSITION METAL COMPLEXES THEREOF AND USES THEREOF IN ASYMMET-  
RIC REACTIONS

(57) Abstract: Chiral ligands and transition metal complexes based on such chiral ligands useful in asymmetric catalysis are dis-  
closed. The chiral ligands include chiral C1-C6 TunaPhos ligands. The ruthenium TunaPhos complex reduces ketones to the corre-  
sponding alcohols with 95-99.6 % enantioselectivity. The transition metal complexes of the chiral ligands are useful in asymmetric  
reactions such as asymmetric hydrogenation, hydride transfer, hydrosilylation, hydroboration, hydrovinylation, hydroformylation,  
hydrocarboxylation, isomerization, allylic alkylation, cyclopropanation, Diels-Alder reaction, Heck reaction, isomerization, Aldol  
reaction, Michael addition and epoxidation reactions.

**CHIRAL PHOSPHINES, TRANSITION METAL COMPLEXES  
THEREOF AND USES THEREOF IN ASYMMETRIC REACTIONS**

5

**BACKGROUND OF THE INVENTION**

1. **FIELD OF THE INVENTION**

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The present invention relates to novel chiral biaryl phosphines and chelating phosphines with tunable bite angles for applications in asymmetric catalysis. More particularly, the present invention relates to transition metal complexes of these ligands, which are useful as catalysts in asymmetric reactions.

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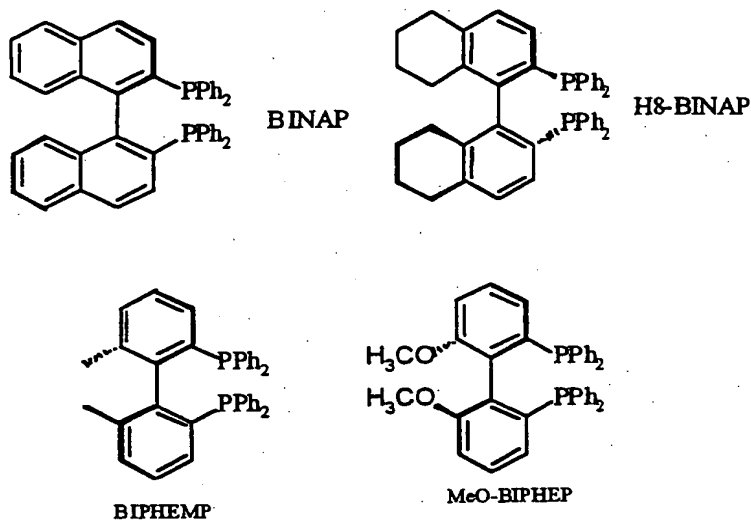
2. **DESCRIPTION OF THE PRIOR ART**

Discovery of new chiral ligands is crucial in developing highly enantioselective transition metal-catalyzed reactions. Despite the large number of chiral ligands that have been made for applications in asymmetric catalysis, only few chiral ligands or synthetic routes or motifs have been commonly used in the synthesis of chiral molecules by the chemical industry or academic laboratories.

Among these ligands, BINAP is one of frequently used chiral ligands. The axially dissymmetric, fully aromatic BINAP have demonstrated to be highly effective for many asymmetric reactions (Noyori, R.; Takaya, H. *Acc. Chem. Res.* 1990, 23, 345; Ohkuma, T.; Koizumi, M.; Doucet, H.; Pham, T.; Kozawa, M.; Murata, K.; Katayama, E.; Yokozawa, T.; Ikariya, T.; Noyori, R. *J. Am. Chem. Soc.* 1998, 120, 13529). Related axially dissymmetric ligands such as MeO-BIPHEP and BIPHEMP were made and used for a number of asymmetric reactions (Schmid, R. *et al. Pure & Appl. Chem.* 1996, 68, 131; Foricher, J.:

Heiser, B.; Schmid, R. US Patent 5,302,738; Michel, L.; European Patent Application 0667350A1; Broger, E. A.; Foricher, J.; Heiser, B.; Schmid, R. PCT WO 92/16536). Several chiral biaryl phosphines known in the literature are depicted below.

5



Despite the extensive research in this area, there are still a variety of  
 10 reactions in which only modest enantioselectivity has been achieved with these  
 ligands. Specially, the free rotation in certain degrees makes BINAP as a  
 conformationally flexible ligand. Recent results suggest that partially hydrogenated  
 BINAP with a bigger bite angle, i.e., H8-BINAP, may be a better ligand in certain  
 asymmetric reactions.

15

For example, restricting conformational flexibility can enhance  
 enantioselectivity (Uemura, T.; Zhang, X.; Matsumura, K.; Sayo, N.;  
 Kumobayashi, H.; Ohta, T.; Nozaki, K.; Takaya, H. *J. Org. Chem.* 1996, 61,  
 5510). For most chiral axially dissymmetric phosphine ligands, there is a low

energy bite angle dictated by the metal species and a large degree of free rotation. The bite angle of chelating chiral phosphines is difficult to fine-tune. Change of ligand electronic properties can also contribute to the activity as well as to the enantioselectivity of a reaction. Because different substrates require different size  
5 of chiral pockets, it is important to have a tunable chiral ligand system to achieve high enantioselectivity.

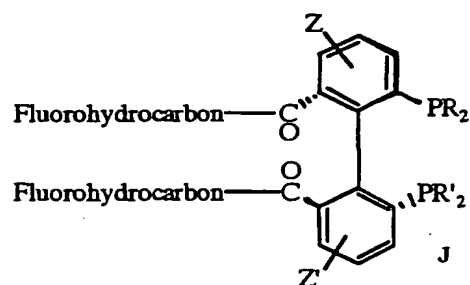
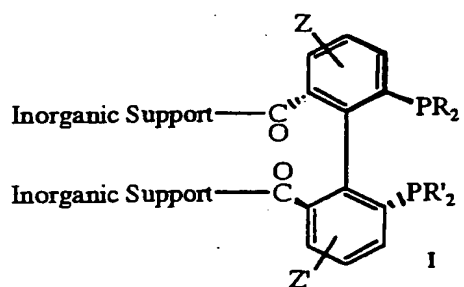
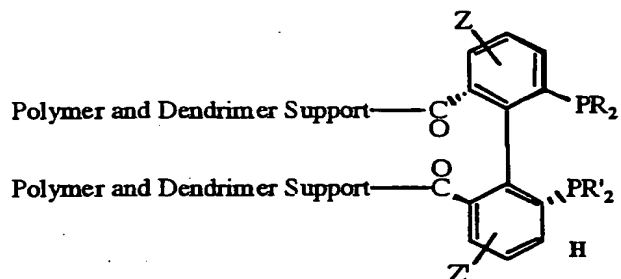
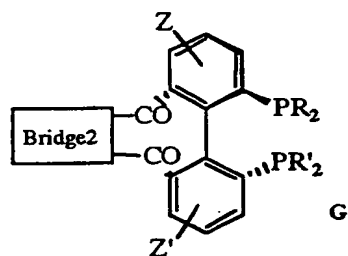
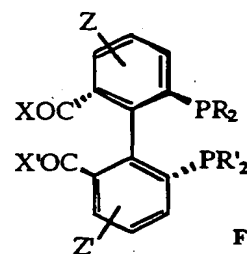
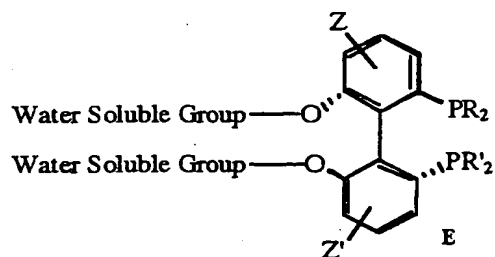
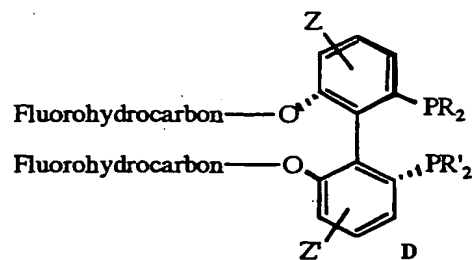
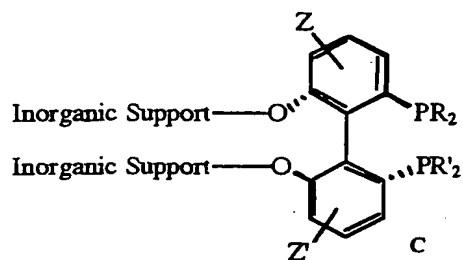
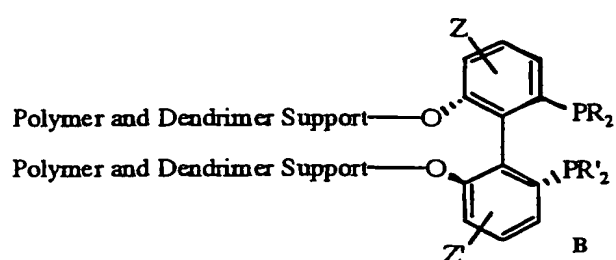
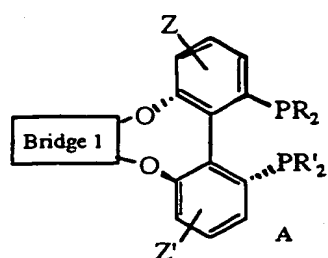
The present invention includes tunable chiral biaryl phosphine ligands with a variety of bite angles by linking two aryl groups with a variety of bridges.  
10 Several new chiral biaryl phosphines are disclosed. To achieve heterogenous and supported catalysts, a number of approaches to ligand systems have been developed. These include linking these ligands to a polymer chain, organic or inorganic supports such as dendrimers, silica gel and molecular sieves. Water-soluble groups can be easily introduced into the ligands and fluorocarbon chains  
15 can be introduced to promote phase separation.

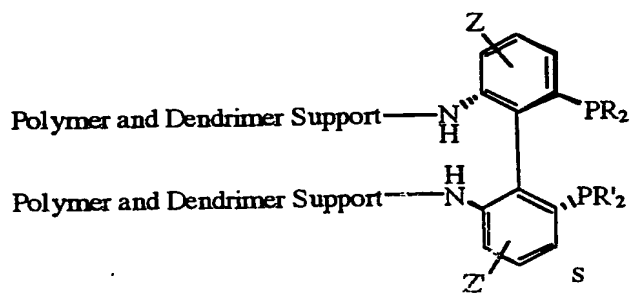
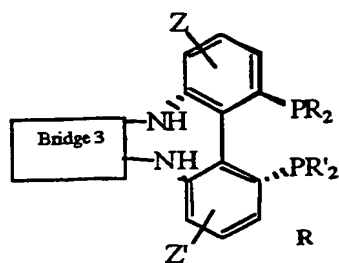
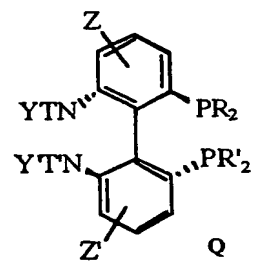
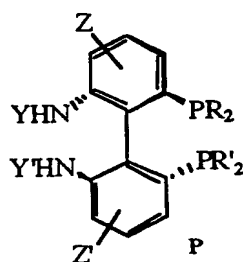
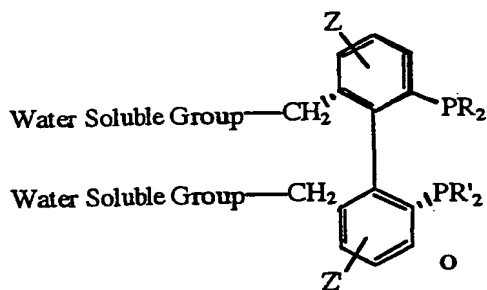
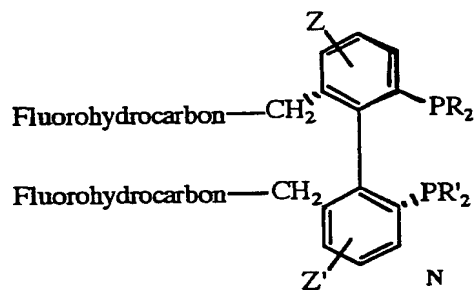
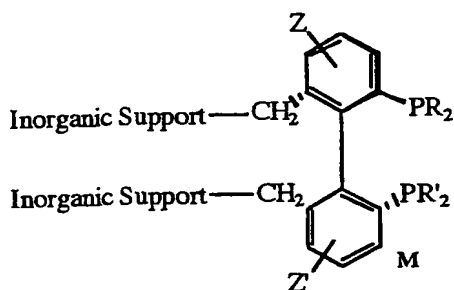
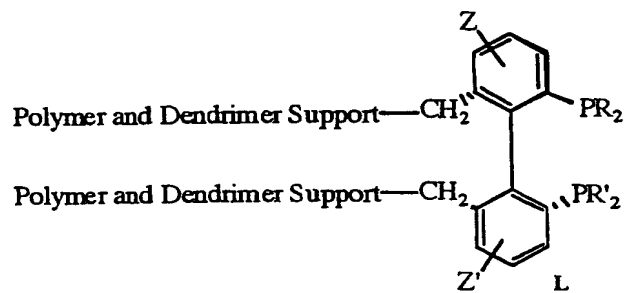
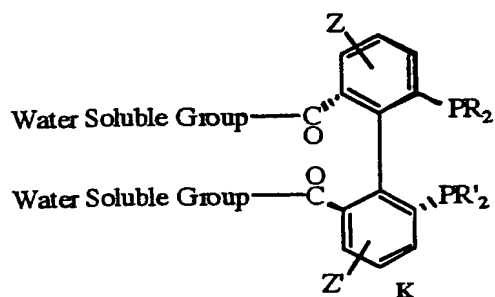
Catalysts derived from the ligands of the present invention are employed in a variety of asymmetric reactions such as hydrogenation, hydride transfer reaction, hydrosilylation, hydroboration, hydrovinylation, hydroformylation,  
20 hydrocarboxylation, isomerization, allylic alkylation, cyclopropanation, Diels-Alder reaction, Aldol reaction, Heck reaction and Michael addition to prepare asymmetric compounds having high enantiomeric purity.

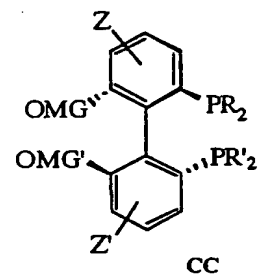
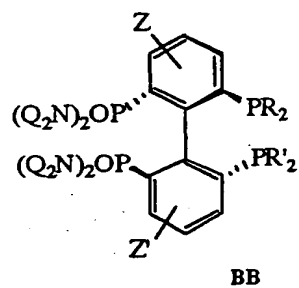
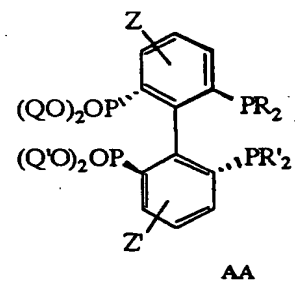
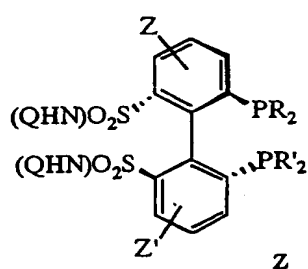
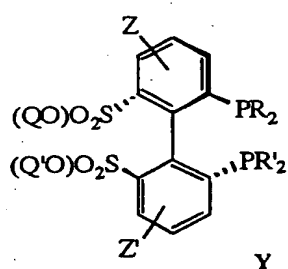
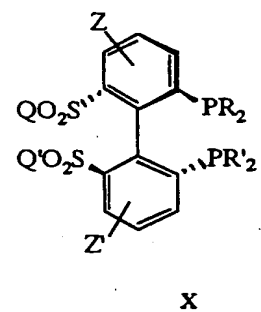
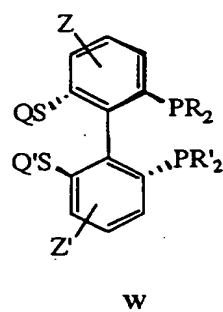
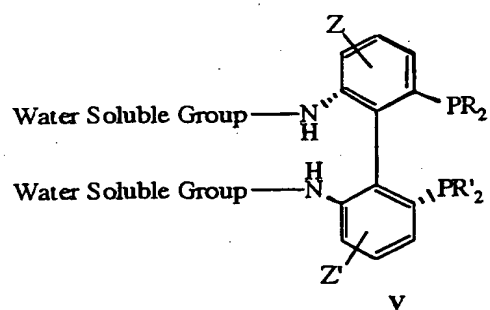
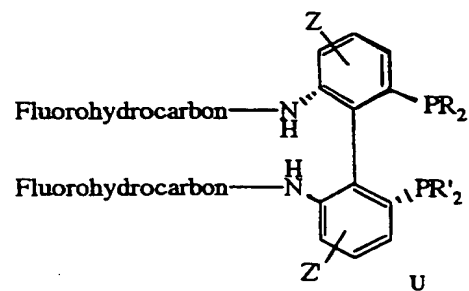
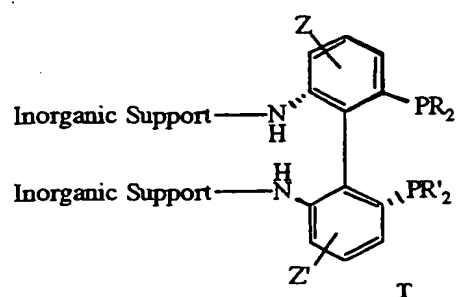
### SUMMARY OF THE INVENTION

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The present invention includes a ligand selected from the group consisting of compounds represented by A through Z, AA, BB and CC:







wherein "bridge 1" is selected from the group consisting of: C=O, C=S, SO<sub>2</sub>, PO(OR<sup>1</sup>), PO(NHR<sup>1</sup>), PO(NR<sup>1</sup>R<sup>2</sup>), divalent phenyl, substituted divalent phenyl, 2,2'-divalent-1,1'-biphenyl, substituted 2,2'-divalent-1,1'-biphenyl, 2,2'-divalent-1,1'-binaphthyl, substituted 2,2'-divalent-1,1'-binaphthyl, 1,1'-ferrocene, substituted 1,1'-ferrocene, SiR<sup>1</sup><sub>2</sub>(CH<sub>2</sub>)<sub>n</sub> where n is an integer ranging from 1 to 8, and (CR<sup>2</sup>)<sub>n</sub>X<sup>1</sup>(CR<sup>2</sup>)<sub>m</sub> wherein each n, m is independently an integer from 1 to 8, wherein X<sup>1</sup> is selected from the group consisting of: O, S, NR<sup>3</sup>, PR<sup>3</sup><sub>2</sub>, <sup>+</sup>NR<sup>3</sup><sub>2</sub>, <sup>+</sup>PR<sup>3</sup><sub>2</sub>, divalent aryl, divalent fused aryl, divalent 5-membered ring heterocyclic group and divalent fused heterocyclic group;

wherein "bridge 2" is selected from the group consisting of: NH, O, a single bond, (CH<sub>2</sub>)<sub>n</sub>, O(CH<sub>2</sub>)<sub>n</sub>O, NH(CH<sub>2</sub>)<sub>n</sub>NH, wherein each n is independently an integer from 1 to 8, divalent phenyl, substituted divalent phenyl, divalent phenyl amine, substituted divalent phenyl amine, 2,2'-divalent-1,1'-biphenyl, substituted 2,2'-divalent-1,1'-biphenyl, 2,2'-divalent-1,1'-binaphthyl, substituted 2,2'-divalent-1,1'-binaphthyl, 1,1'-ferrocene, substituted 1,1'-ferrocene, O(CR<sup>2</sup>)<sub>n</sub>X<sup>1</sup>(CR<sup>2</sup>)<sub>m</sub>O, NH(CR<sup>2</sup>)<sub>n</sub>X<sup>1</sup>(CR<sup>2</sup>)<sub>m</sub>NH and (CR<sup>2</sup>)<sub>n</sub>X<sup>1</sup>(CR<sup>2</sup>)<sub>m</sub> wherein each n, m is independently an integer from 1 to 8, wherein X<sup>1</sup> is selected from the group consisting of: O, S, NR<sup>3</sup>, PR<sup>3</sup><sub>2</sub>, <sup>+</sup>NR<sup>3</sup><sub>2</sub>, <sup>+</sup>PR<sup>3</sup><sub>2</sub>, divalent aryl, divalent fused aryl, divalent 5-membered ring heterocyclic group and divalent fused heterocyclic group;

wherein "bridge 3" is selected from the group consisting of: SO<sub>2</sub>, CO, COCO, OC(CH<sub>2</sub>)<sub>n</sub>CO, (CH<sub>2</sub>)<sub>n</sub> wherein n is an integer ranging from 1 to 8, COArCO, wherein Ar is selected from the group consisting of: divalent phenyl, substituted divalent phenyl, 2,2'-divalent-1,1'-biphenyl, substituted 2,2'-divalent-1,1'-biphenyl, 2,2'-divalent-1,1'-binaphthyl, substituted 2,2'-divalent-1,1'-binaphthyl, 1,1'-ferrocene, substituted 1,1'-ferrocene and CO(CR<sup>2</sup>)<sub>n</sub>X<sup>1</sup>(CR<sup>2</sup>)<sub>m</sub>CO wherein each n, m is independently an integer from 1 to 8, wherein X<sup>1</sup> is selected from the group consisting of: O, S, NR<sup>3</sup>, PR<sup>3</sup><sub>2</sub>, <sup>+</sup>NR<sup>3</sup><sub>2</sub>, <sup>+</sup>PR<sup>3</sup><sub>2</sub>, divalent aryl, divalent fused aryl, divalent 5-membered ring heterocyclic group and divalent fused heterocyclic group;



wherein each  $R^1$  is independently selected from the group consisting of: aryl, alkyl, alkaryl, aralkyl and substituted derivatives thereof wherein the substituent in said substituted derivatives is selected from the group consisting of: carboxylic acid, alkoxy, hydroxy, alkylthio, thiol and dialkylamino;

5            wherein each  $R^2$  and  $R^3$  is independently selected from the group consisting of: aryl, alkyl, substituted aryl and substituted alkyl group;

             wherein each said substituted divalent phenyl, divalent phenyl amine, biphenyl, binaphthyl and ferrocene derivative comprises at least one substituent selected from the group consisting of aryl, substituted aryl, alkyl, heteroatom, F, Cl, Br, I,  $COOR^1$ ,  $SO_3R^1$ ,  $PO_3R^{1,2}$ ,  $OR^1$ ,  $SR^1$ ,  $PR^{1,2}$ ,  $AsR^{1,2}$ ,  $SbR^{1,2}$ , OAr, nitro, 10 amino, vinyl, substituted vinyl and sulfonic acid;

             wherein each R and R' is independently selected from the group consisting of: aryl, alkyl, alkaryl, aralkyl and substituted derivatives thereof, wherein the substituent in said substituted derivatives is selected from the group consisting of: 15 carboxylic acid, alkoxy, hydroxy, alkylthio, thiol, dialkyl amino groups;

             wherein each X and X' is independently selected from the group consisting of: aryl, alkyl, alkaryl, aralkyl, alkoxy, alkoxy, hydroxy, alkylthio, thiol, primary amine, secondary amine and  $ArNH$ ;

             wherein each Z and Z' is independently selected from the group consisting of: halogen, alkyl, aryl, aryloxy, nitro, amino, vinyl, substituted vinyl and sulfonic acid; and 20

             wherein each Q, Q', Y, Y', T and T' is independently selected from the group consisting of: aryl, alkyl, alkaryl, aralkyl and substituted derivatives thereof, wherein the substituent in said substituted derivatives is selected from the group 25 consisting of: carboxylic acid, alkoxy, hydroxy, alkylthio, thiol and dialkylamino.

             The present invention further includes a catalyst prepared by a process comprising contacting a transition metal salt, or a complex thereof, and a ligand selected from the group consisting of compounds represented by A through Z, 30 AA, BB and CC, as described above.

The present invention still further includes a process for preparation of an asymmetric compound using a catalyst according to the present invention. The process comprises contacting a substrate capable of forming an asymmetric product by an asymmetric reaction and a catalyst prepared by a process comprising

5 contacting a transition metal salt, or a complex thereof, and a ligand selected from compounds represented by A through Z, AA, BB and CC, as described above. The transition metal complexes of the chiral ligands of the present invention produce chiral products with an extremely high enantioselectivity. For example, ruthenium complex of chiral C4-TunaPhos ligand reduces isopropyl acetoacetate

10 with 99% enantioselectivity to produce the corresponding alcohol in a 99% ee.

#### **DETAILED DESCRIPTION OF INVENTION**

This invention covers several new families of chiral biaryl phosphines. One

15 family of chiral phosphines has a bridge to link two aryl groups such that rotation between the Sp<sup>2</sup>-Sp<sup>2</sup> aryl-aryl bond is limited. Another family of chiral phosphines has substituents in the aryl backbone including amines and carboxylates. The steric and electronic properties of these ligands are different from those in BINAP or MeO-BIPHEP ligands. Organic, inorganic and polymer-supported biphasic

20 catalysts are also included. The chiral catalysts of the present invention are useful in a variety of transition metal-catalyzed asymmetric reactions. The various types of ligands of the present invention are described below.

For each class of A to Z, AA, BB and CC ligands, the corresponding

25 enantiomer, as well as enantiomeric mixtures, are also contemplated. A represents chelating chiral phosphines derived from MeO-BIPHEP and related compounds, which has a bridge between two phenol unites. B and C include chiral biaryl phosphines with polymer, dendrimer and inorganic supports through the two oxygen atoms. D and E cover chiral biaryl phosphines with substituted

30 fluorohydrocarbons or water-soluble groups. F type of ligands represent a new class of chiral biaryl phosphines with carboxylates in the 1, 1' position and G type

of ligands has a bridge linked two carbonyls groups in the biaryl phosphine. Type H to K ligands have polymer supports, dendrimer supports, inorganic supports, fluorosubstituted hydrocarbons and water-soluble groups. The linkage to the chiral biaryl ligands is a carbonyl group. Type L to O ligands have a methylene linker to polymer supports, dendrimer supports, inorganic supports, fluorine-substituted hydrocarbons and water-soluble groups. Type N' ligands have a CF<sub>2</sub> linker to fluorosubstituted hydrocarbons. Type P and Q ligands include chiral biaryl phosphines with nitrogen substituents in the 1, 1' position. Type R ligands have a bridge linked to two nitrogen groups. Type S to V ligands have nitrogen linkers to connect polymer supports, dendrimer supports, inorganic supports, fluorosubstituted hydrocarbons and water-soluble groups. Type W to Z ligands contain sulfur groups in the 1,1' position of the chiral biaryl phosphines. Type AA to BB include phosphine groups in the 1,1' position of the chiral biaryl phosphines. Type CC ligands have ortho-directed metallation groups (OMG).

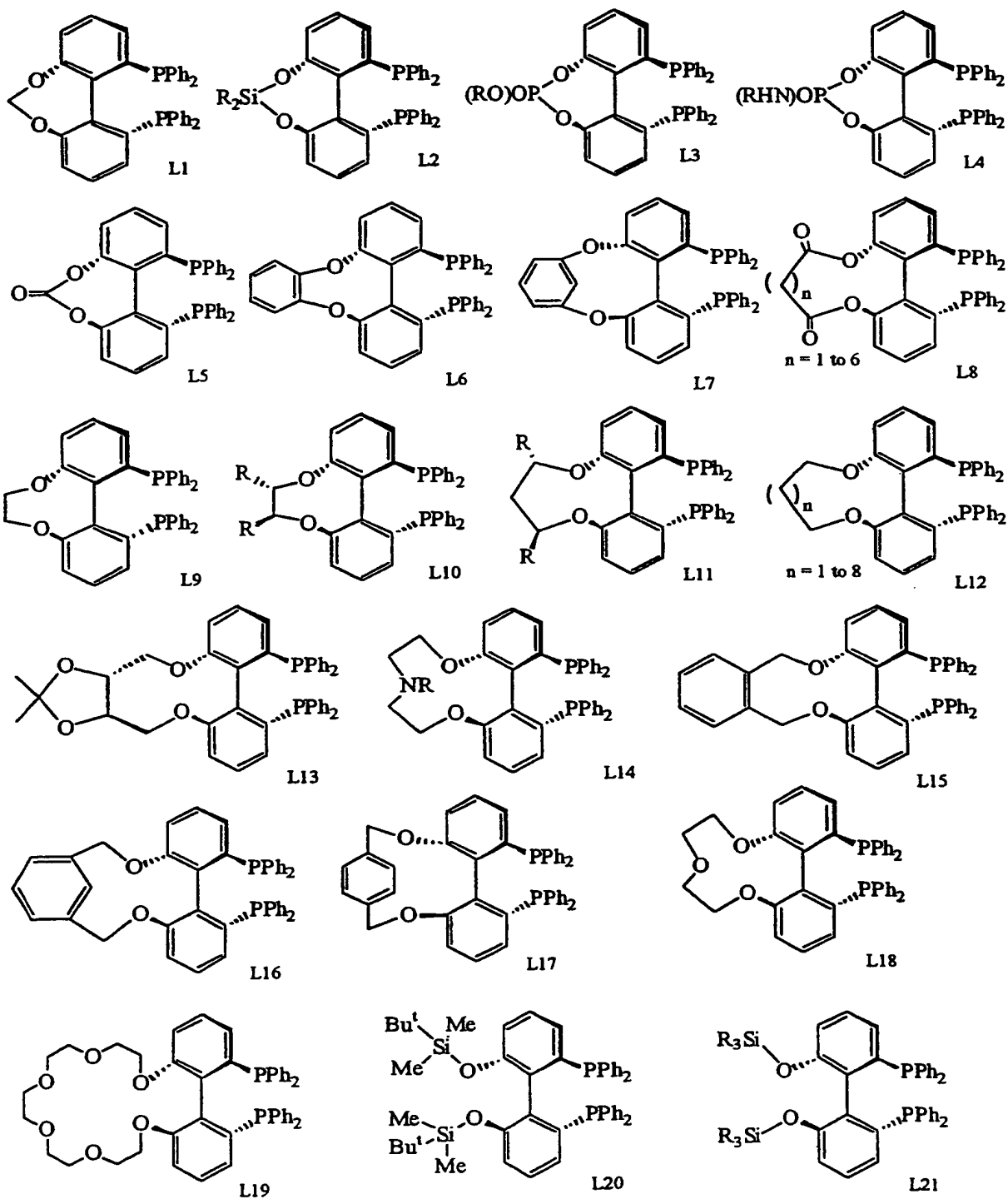
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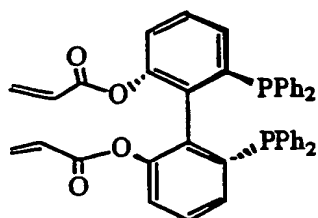
The ligand of the present invention can be used in the monomeric form or in a polymeric or copolymeric form, either as a free ligand or as a ligand supported on a support material. Preferably, the support material is either a polymer support, such as, polystyrene, polyacrylate, resin, PEG, MeO-PEG, dendritic polyester or dendritic polyenamide, or the support material is an inorganic support, such as, silica, alumina, zeolite, molecular sieve or mesoporous material. The ligand may be attached to the support material through physical interactions or it can be linked to the support material by a linker group, such as,  $\text{NH}(\text{CH}_2)_n\text{Si}(\text{OEt})_3$  wherein  $n = 1$  to 8,  $\text{CO}(\text{CH}_2)_n\text{Si}(\text{OEt})_3$ ,  $(\text{CH}_2)_n\text{Si}(\text{OEt})_3$ , C-O, C-N and  $\text{NCF}_2$  linker. The ligand may be substituted by at least one water-soluble functional group, such as, sulfuric, phosphoric, carboxylic, quaternary ammonium and MeO-PEG groups.

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The preferred ligands of the present invention are selected from ligands designated A through Z, AA, BB and CC, which include members represented by the formula L1 through L102, as depicted below:

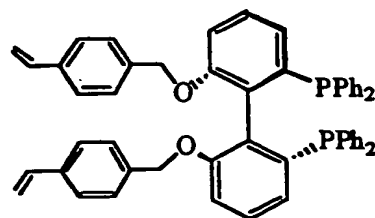
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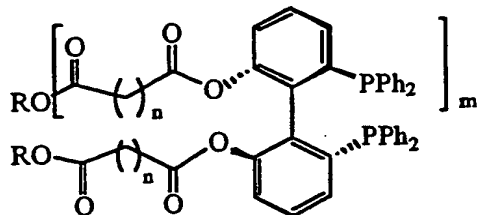
L22

Polyacrylate

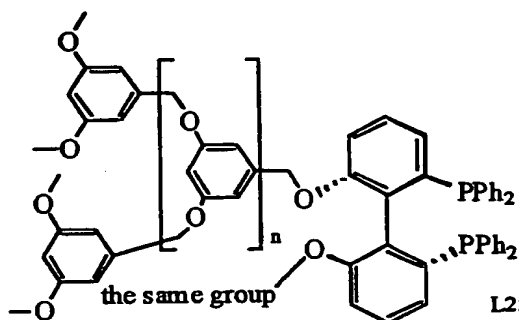


L23

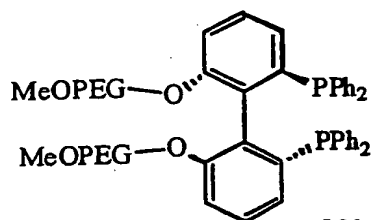
Polystyrene



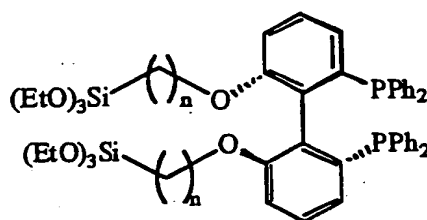
L24



L25



L26

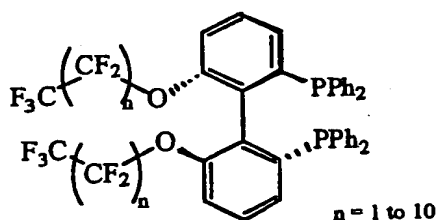


L27

SiO2 Support

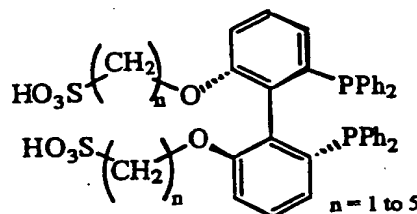
Zeolite Support

Mesoporous Materials



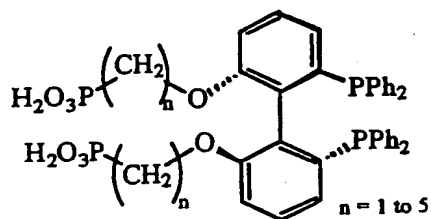
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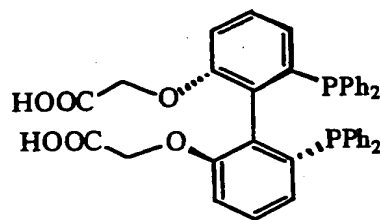
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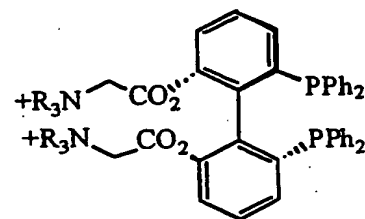


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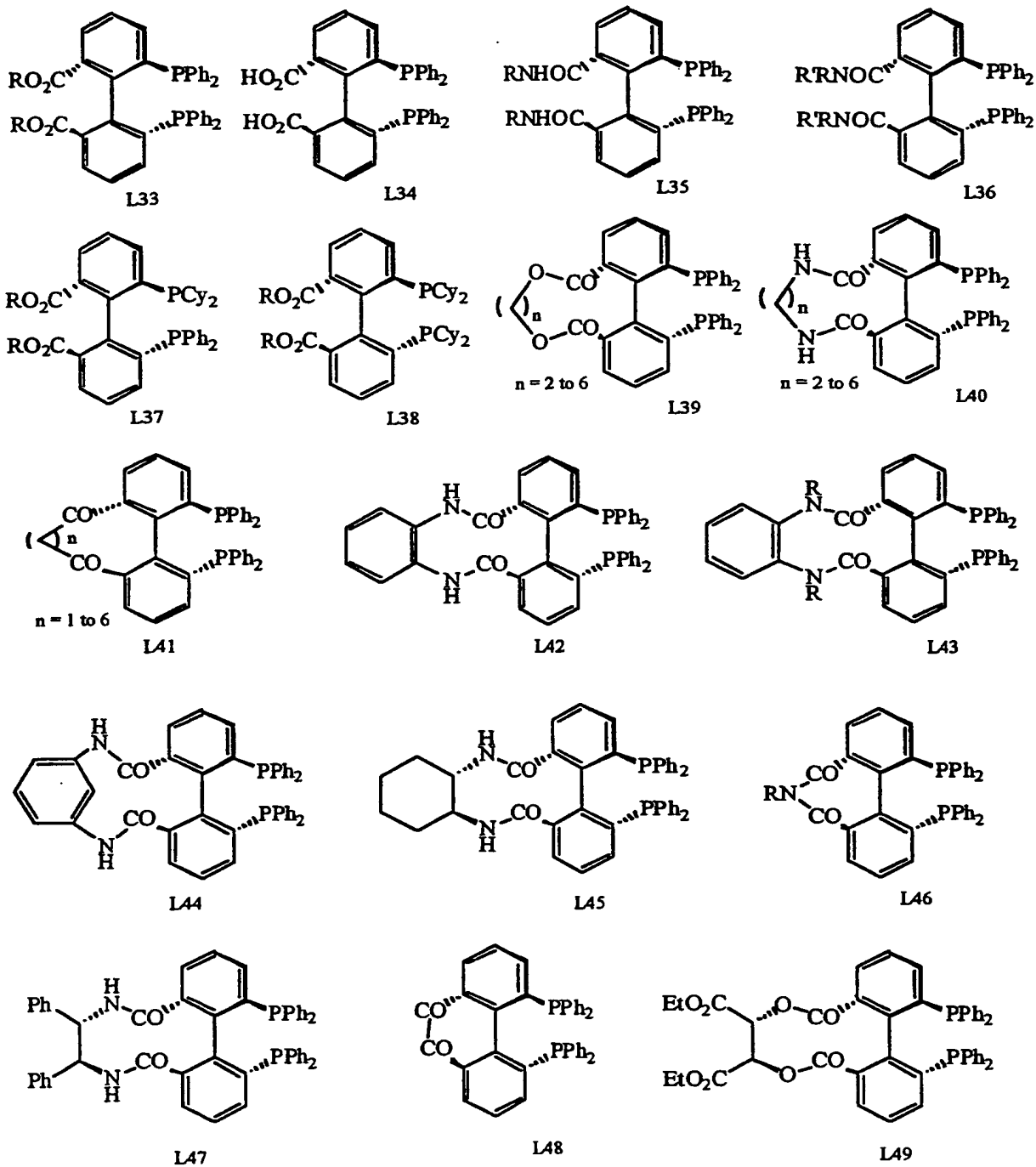
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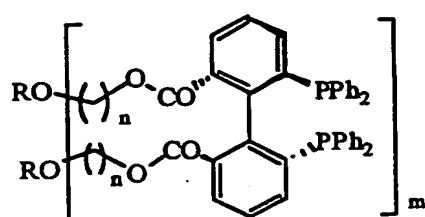


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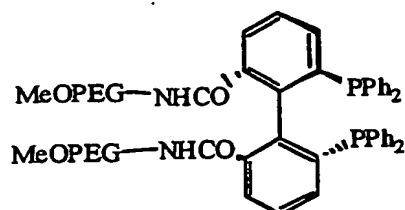


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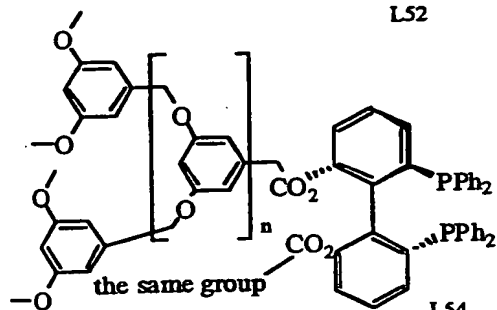




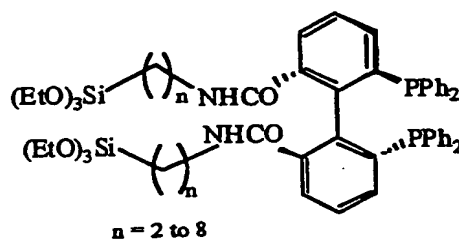
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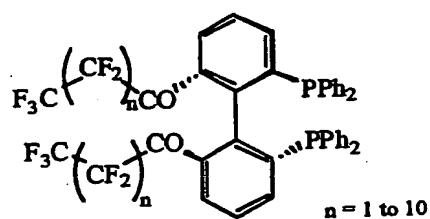


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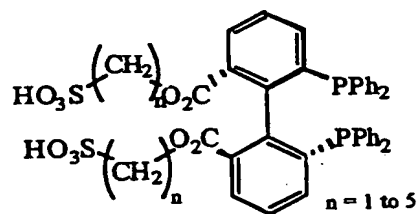


SiO<sub>2</sub> Support  
Zeolite Support  
Mesoporous  
Materials

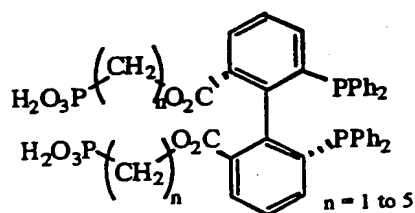
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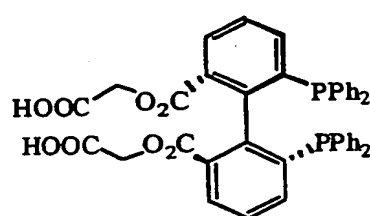
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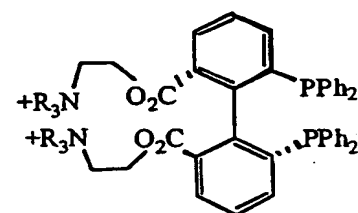
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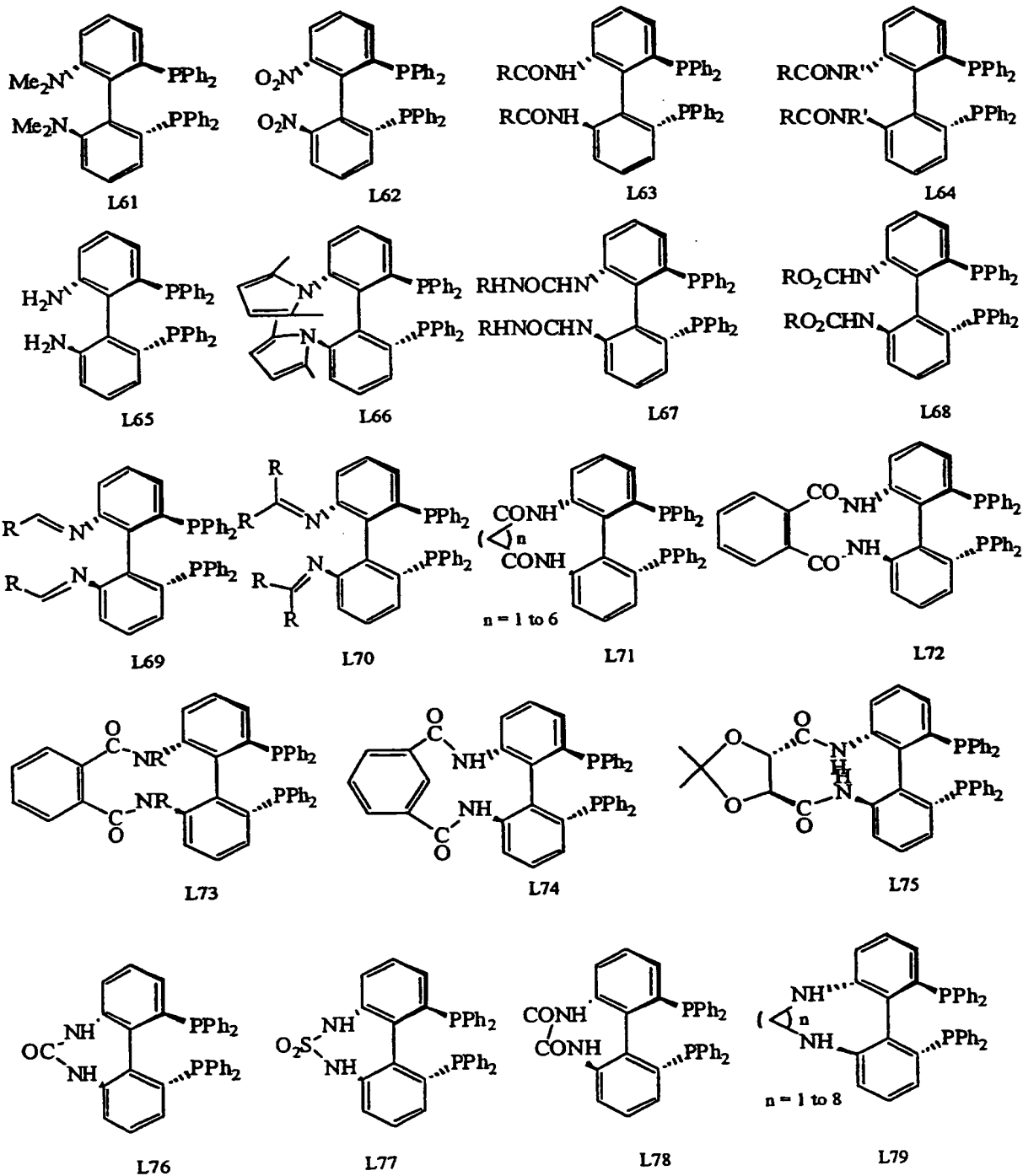
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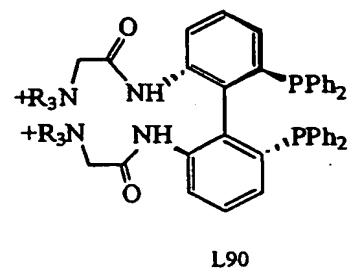
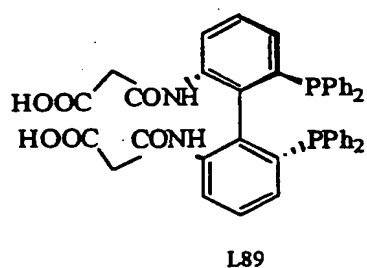
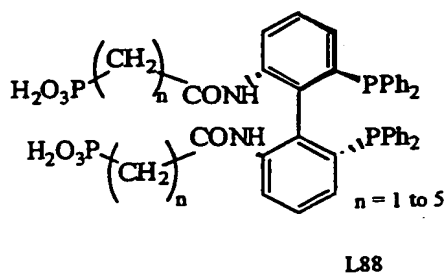
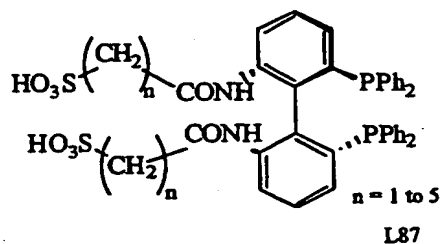
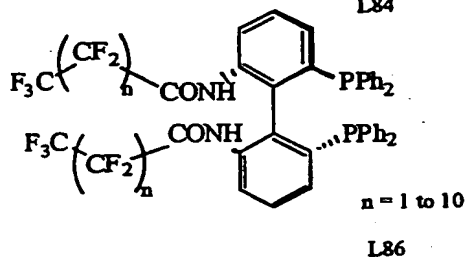
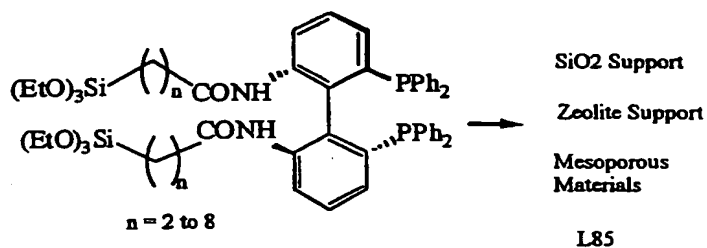
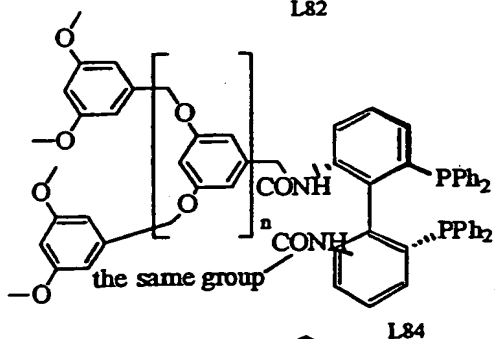
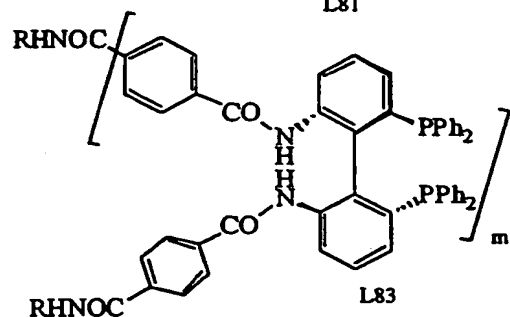
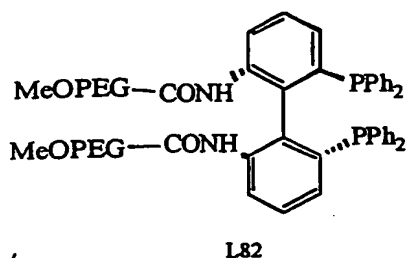
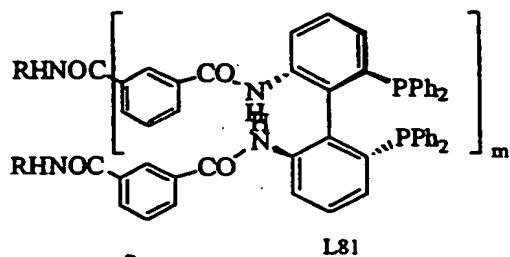
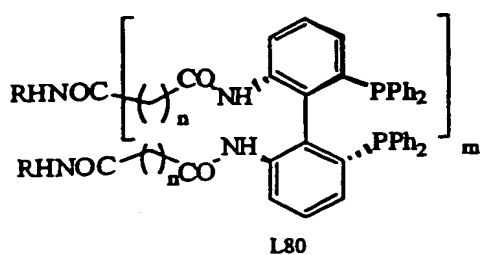
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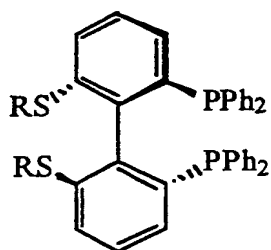


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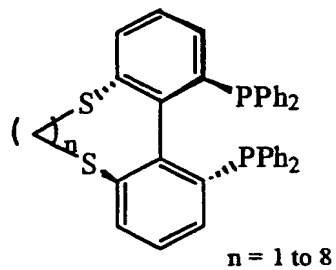






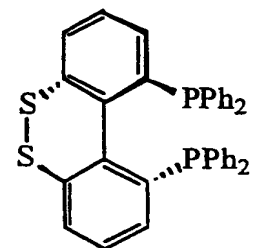


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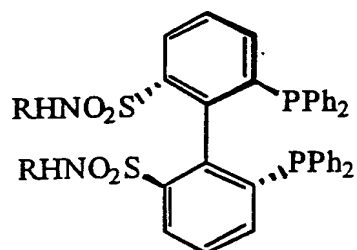


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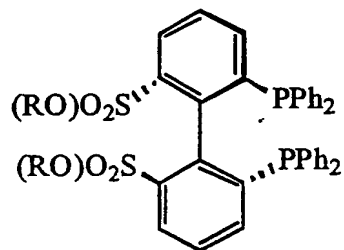
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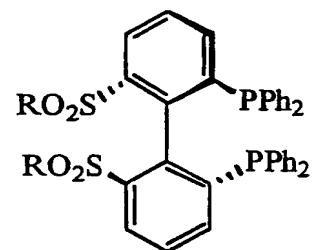
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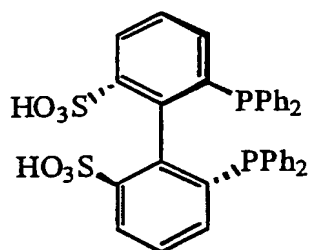
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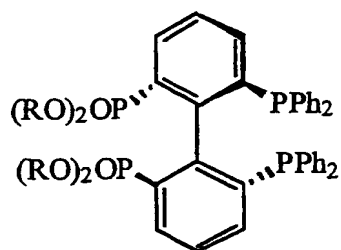
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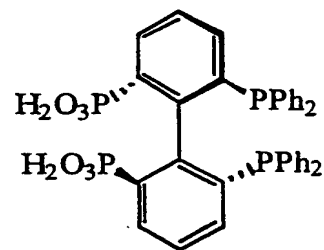
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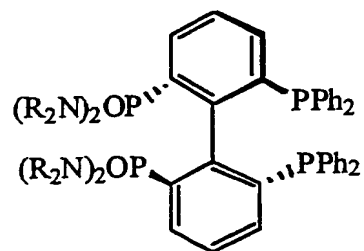
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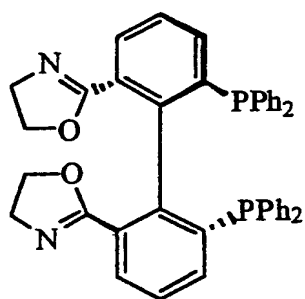
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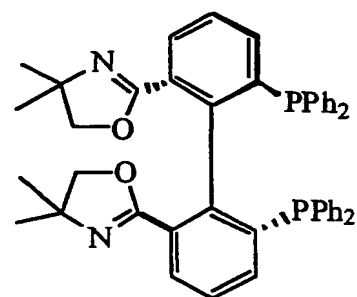
L99



L100



L101



L102

The ligand may be linked to an inorganic support by any conventional links, such as,  $\text{NH}(\text{CH}_2)_n\text{Si}(\text{OEt})_3$ ,  $\text{CO}(\text{CH}_2)_n\text{Si}(\text{OEt})_3$ ,  $(\text{CH}_2)_n\text{Si}(\text{OEt})_3$  ( $n = 1$  to  $8$ ).

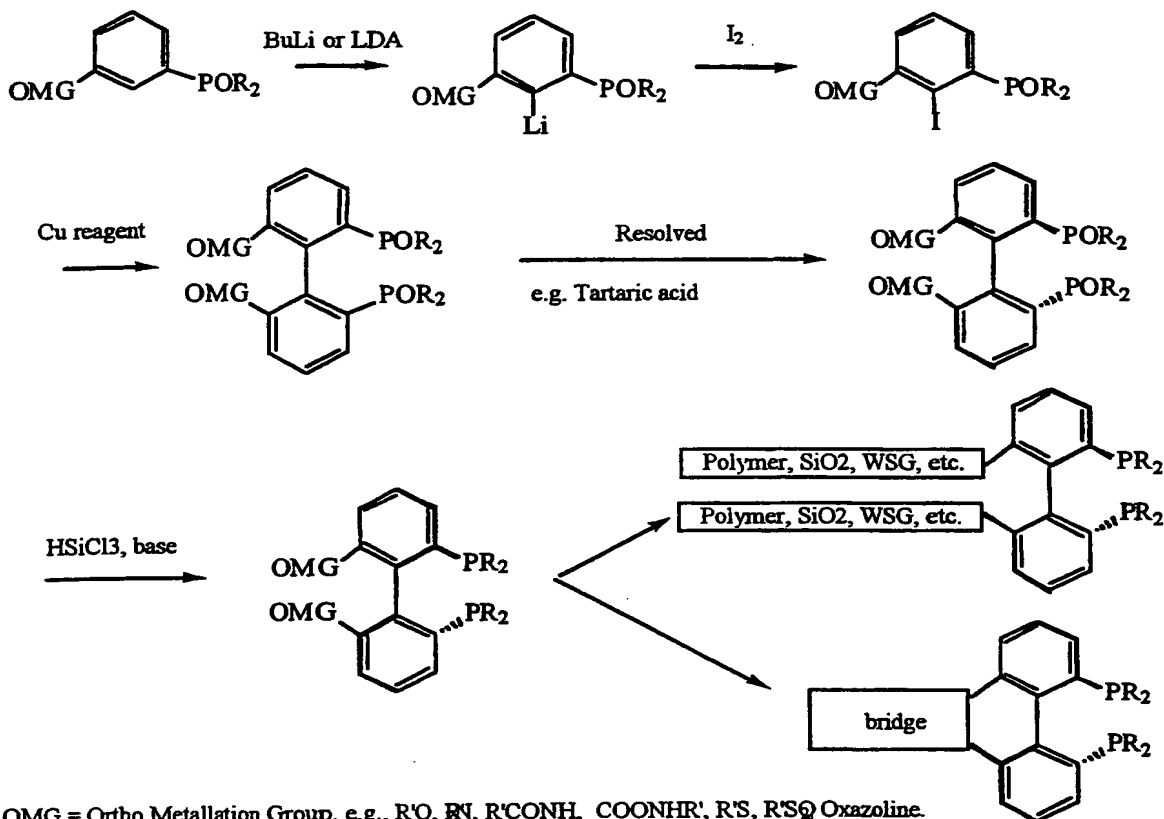
Selective hydrolysis leads to inorganic supported ligands and catalysts. The ligand can have water-soluble functional groups, such as,  $\text{R}''\text{SO}_3^-$ ,  $\text{R}''\text{PO}_3^{2-}$ ,  $\text{R}''\text{COO}^-$ , a quaternary ammonium group and MeO-PEG, wherein  $\text{R}''$  is a ligand residue. The counterions include alkali, alkaline earth metals, ammonium, halogens and triflate (Otf).

Generally, no single chiral ligand is suitable for use in all asymmetric reactions. Even with the most widely used chiral biaryl diphosphine BINAP, fine-tuning is necessary to obtain high enantiomeric excess (ee) in specific reactions. Ligands with similar stereo and electronic factors, but with different bite angles, behave dramatically differently in some reactions. For example, Kamer, P. C. J.; Reek, J. N. H. and van Leeuwen, P. W. N. M. *Chemtech*, 1998, 28(9), 27 report that in Leeuwen's nickel catalyzed hydrocyanation of styrene, the reactivity and selectivity are good only if the bite angle is in the range from  $101^\circ$  to  $109^\circ$ . Therefore, design and synthesis of new ligands has always been necessary to provide high ee in selected reactions.

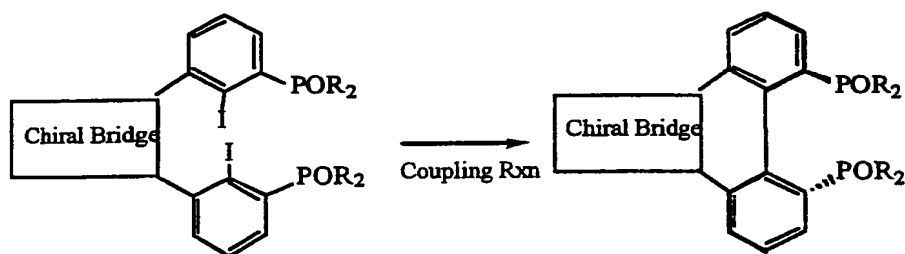
Although chiral biaryl diphosphines such as BINAP, BIPHEMP, and MeO-BIPHEP are efficient ligands for some reactions, there is little or no tunability of their natural bite angle. Applications for asymmetric reactions for a wide variety of reactions and substrate are limited. Such a drawback has now been overcome by bridging the diaryl backbone with a variable length chain. For example, MeO-PHEP is an excellent starting material to construct such a bridge. After demethylation of enantiomerically pure MeO-PHEP, the dihydroxy diphosphine can react with alkyl dihalides in the presence of excess of anhydrous  $\text{K}_2\text{CO}_3$  in DMF and give the desired products 1 to 6.

Synthetic routes to some chiral ligands according to the present invention are outlined below.

## Method A



## Method B



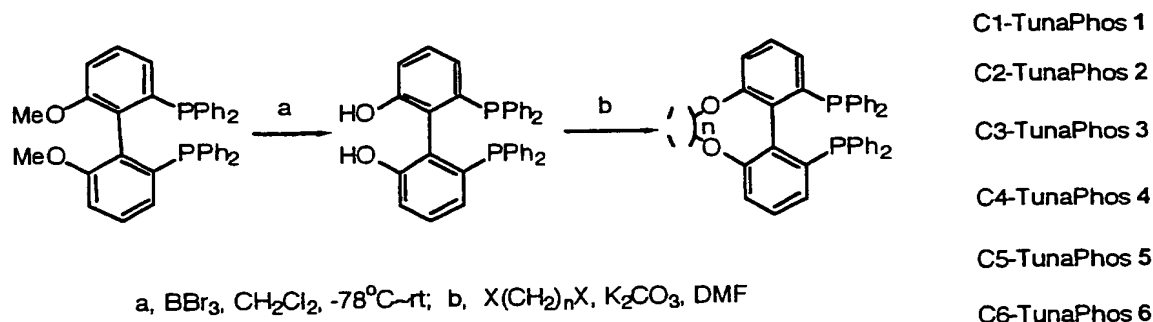
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For example, MeO-PHEP is an excellent starting material to construct such a bridge. After demethylation of enantiomerically pure MeO-PHEP, the dihydroxy diphosphine can react with alkyl dihalides in the presence of excess of anhydrous  $K_2CO_3$  in DMF and give the desired products 1 to 6.

This family of phosphine ligands, here after "TunaPhos," includes members having a  $C_n$  variable length chain bridge, wherein  $C_n$  represents the number of carbon atoms in the variable length chain bridge and  $n$  is an integer. Examples of TunaPhos include TunaPhos 1 through 6, wherein the variable length chain has 1-6 carbon atoms. The calculated dihedral angles of the  $C_n$ -TunaPhos are calculated based on CAChe, MM2 program. The results of the calculations are summarized in Scheme 1 below.

20

Scheme 1



	c1	c2	c3	c4	c5	c6	TunaPhos
Natural Dihedral Angle	60	74	77	88	94	106	

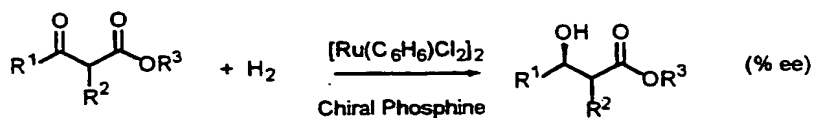
The effect of bite angle for a reaction, asymmetric hydrogenation of  $\beta$ -ketoesters was carried out. The catalyst was made in situ by mixing  $(\text{Ru}(\text{benzene})\text{Cl}_2)_2$  and diphosphine ligand in hot DMF (see Kitamura, M.; Tokunaga, M.; Ohkuma, T. and Noyori, R. *Tetrahedron Lett.* 1991, 32, 4163). The reactivity did not show any difference with C1 to C6 TunaPhos, but the enantioselectivity did change.

10

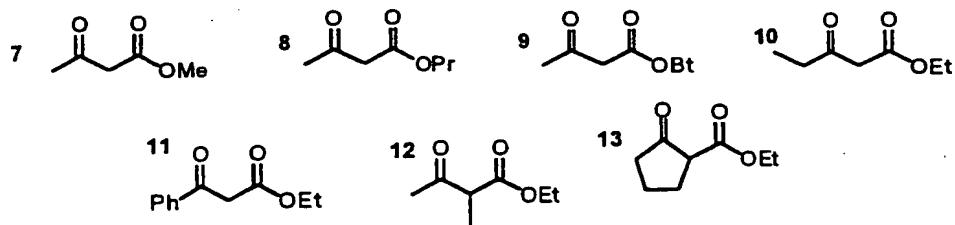
For example, when methyl acetoacetate 7 was used as the substrate and C1 or C2-TunaPhos was used as the ligand, the enantioselectivity was only about 91%. With C3-TunaPhos, the ee increased to almost 98%. The best ee (>99%) was obtained with C4-TunaPhos. With C5 and C6-TunaPhos, ee values decreased (Entry 1, Table 1). Clearly, C4-TunaPhos is a preferred ligand for hydrogenation of these types of substrates.

15

Table 1

7 R<sup>1</sup>=Me, R<sup>2</sup>=H, R<sup>3</sup>=Me8 R<sup>1</sup>=Me, R<sup>2</sup>=H, R<sup>3</sup>=Pri9 R<sup>1</sup>=Me, R<sup>2</sup>=H, R<sup>3</sup>=But10 R<sup>1</sup>=Et, R<sup>2</sup>=Me, R<sup>3</sup>=Et11 R<sup>1</sup>=Ph, R<sup>2</sup>=H, R<sup>3</sup>=Et12 R<sup>1</sup>=Me, R<sup>2</sup>=Me, R<sup>3</sup>=Et13 R<sup>1</sup>,R<sup>2</sup>=(CH<sub>2</sub>)<sub>3</sub>, R<sup>3</sup>=Et

Sub.	Cat. 1	2	3	4	5	6	BINAP	MEOPHEP
7	90.9	90.8	97.7	99.1	97.1	96.5	98.4	97.9 %ee
8	90.1	90.8	97.7	99.3	96.8	96.3	98.2	98.8
9	90.0	93.9	99.0	99.2	96.8	95.9	97.6	98.5
10	89.9	93.8	99.0	99.0	96.9	95.9	97.5	98.5
11	76.8	71.4	72.0	82.3	78.5	60.5	78.4	74.8
12	87.9	89.7	95.2	96.8	94.7	91.9	93.4	97.5
13	79.6	85.6	95.5	95.8	92.5	90.7	91.3	95.2
	(46.1 cis)	(45.7)	(45.5)	(45.6)	(44.2)	(46.5)	(46.8)	(45.9)
	93.9 (53.9 trans)	95.6 (54.3)	98.5 (54.5)	98.7 (54.4)	98.0 (55.8)	97.5 (53.5)	95.7 (53.2)	98.1 (54.1)



Based on the above results, the pronounced effect of the bite angle on the enantioselectivity in asymmetric hydrogenation of  $\beta$ -ketoesters is confirmed. With other types of substrates or reactions, a different bite angle and therefore, a different TunaPhos might be preferred.

5

The ligand according to the present invention can be racemic, i.e., racemic mixture of enantiomers, or a non-racemic mixture of enantiomers. Preferably, the ligand according to the present invention is one of the enantiomers. When the ligand is a non-racemic mixture of enantiomers, preferably it has an optical purity  
10 of at least 85% ee, more preferably, it has an optical purity of at least 95% ee.

The present invention also includes a catalyst prepared by a process comprising contacting a transition metal salt, or a complex thereof, and a ligand selected from the group consisting of compounds represented by A through Z,  
15 AA, BB and CC.

As for the ligand, the catalyst according to the present invention can be racemic, such as, a racemic mixture of enantiomers, or it can be a non-racemic mixture of enantiomers. Preferably, the catalyst according to the present invention  
20 is one of the enantiomers. When the ligand according to the present invention is a non-racemic mixture of enantiomers, preferably it has an optical purity of at least 85% ee, more preferably, it has an optical purity of at least 95% ee.

Suitable transition metals for the preparation of the catalyst include Pt, Pd,  
25 Rh, Ru, Ir, Cu, Ni, Mo, Ti, V, Re and Mn.

The catalyst can be prepared by contacting a transition metal salt or its complex and a ligand selected from A through Z, AA, BB and CC. The transition metal salt or complex can be  $\text{PtCl}_2$ ;  $\text{Pd}_2(\text{DBA})_3$ ;  $\text{Pd}(\text{OAc})_2$ ;  $\text{PdCl}_2(\text{RCN})_2$ ;  
30  $(\text{Pd}(\text{allyl})\text{Cl})_2$ ;  $(\text{Rh}(\text{COD})\text{Cl})_2$ ;  $(\text{Rh}(\text{COD})_2)\text{X}$ ;  $\text{Rh}(\text{acac})(\text{CO})_2$ ;  $\text{Rh}(\text{ethylene})_2(\text{acac})$ ;  
 $\text{Rh}(\text{CO})_2\text{Cl}_2$ ;  $\text{Ru}(\text{RCOO})_2(\text{diphosphine})$ ;  $\text{Ru}(\text{methylallyl})_2(\text{diphosphine})$ ;  $\text{Ru}(\text{aryl})$



group) $X_2$ (diphosphine);  $RuCl_2(COD)$ ;  $(Rh(COD)_2)X$ ;  $RuX_2$ (diphosphine);  
 $RuCl_2(=CHR)(PR'_3)_2$ ;  $Ru(ArH)Cl_2$ ;  $Ru(COD)(methylallyl)_2$ ;  $(Ir(COD)_2Cl)_2$ ;  
 $(Ir(COD)_2)X$ ;  $Cu(OTf)$ ;  $Cu(OTf)_2$ ;  $Cu(Ar)X$ ;  $CuX$ ;  $NiX_2$ ;  $Ni(COD)_2$ ;  
 $MoO_2(acac)_2$ ;  $Ti(OiPr)_4$ ;  $VO(acac)_2$ ;  $MeReO_3$ ;  $MnX_2$  or  $Mn(acac)_2$ ; wherein each  
 5 R and R' can independently be alkyl or aryl; Ar is an aryl group; and X is a  
 counteranion. The preferred counteranions include halogen,  $BF_4$ ,  $B(Ar)_4$  wherein  
 Ar is 3,5-di-trifluoromethyl-1-phenyl,  $ClO_4$ ,  $SbF_6$ ,  $CF_3SO_3$ ,  $RCOO$  and a mixture  
 thereof.

10 The catalyst may be prepared in situ or as an isolated compound. An  
 example of the preferred catalyst of the present invention is chiral ruthenium C4-  
 TunaPhos catalyst.

In another aspect, the present invention includes a process for preparation  
 15 of an asymmetric compound using the catalysts described above. The process  
 includes the step of contacting a substrate capable of forming an asymmetric  
 product by an asymmetric reaction and a catalyst prepared by contacting a  
 transition metal salt, or a complex thereof, and a ligand selected from ligands  
 represented by A through Z, AA, BB and CC.

20 Suitable asymmetric reactions include hydrogenation, hydride transfer,  
 hydrosilylation, hydroboration, hydrovinylation, hydroformylation,  
 hydrocarboxylation, isomerization, allylic alkylation, cyclopropanation, Diels-Alder  
 reaction, Heck reaction, isomerization, Aldol reaction, Michael addition and  
 25 epoxidation.

Preferably, the asymmetric reaction is hydrogenation and the substrate to  
 be hydrogenated is an ethylenically unsaturated compound, imine, ketone, enamine,  
 enamide, and vinyl ester. Suitable catalysts for the hydrogenation of ketones to  
 30 produce a chiral alcohol include chiral ruthenium C1 through C6 TunaPhos,  
 particularly C4-TunaPhos catalyst.

## EXAMPLES

### General Procedures

5

All reactions and manipulations were performed in a nitrogen-filled glove box or using standard Schlenk techniques. THF and toluene were dried and distilled from sodium-benzophenone ketyl under nitrogen. Methylene chloride was distilled from  $\text{CaH}_2$ . Methanol was distilled from Mg under nitrogen. (R, R)-BDNPB was made a solution of 10mg/ml in toluene before use. Column chromatography was performed using EM silica gel 60 (230~400 mesh).  $^1\text{H}$ ,  $^{13}\text{C}$  and  $^{31}\text{P}$  NMR were recorded on Bruker WP-200, AM-300, and AMX-360 spectrometers. Chemical shifts were reported in ppm down field from tetramethylsilane with the solvent resonance as the internal standard. Optical rotation was obtained on a Perkin-Elmer 241 polarimeter. MS spectra were recorded on a KRATOS mass spectrometer MS 9/50 for LR-EI and HR-EI. GC analysis was carried on Hewlett-Packard 6890 gas chromatography using chiral capillary columns. HPLC analysis was carried on Waters<sup>TM</sup> 600 chromatography.

20

### EXAMPLE 1

#### Preparation of Ligands

25 (R)-(6,6-Dimethoxybiphenyl-2,2'-diyl) bis(diphenylphosphine) ((R)-MeO-BIPHEP):

To a suspension of (R)-(6,6'-Dimethoxybiphenyl-2,2'-diyl) bis(diphenylphosphine oxide) (46.0 g, 74.9 mmol) in dry *p*-xylene (490 mL) were added  $\text{Bu}_3\text{N}$  (157 mL, 660 mmol) and  $\text{HSiCl}_3$  (57.1 g, 420 mmol) at room temperature under  $\text{N}_2$  with stirring. After stirred at room temperature for 30 min.,

the mixture was heated to refluxing for 3 h. The mixture was then cooled to 0°C and 30% aq. NaOH (350 mL, degassed) was added slowly to the mixture. CH<sub>2</sub>Cl<sub>2</sub> (200 mL, degassed) was added and the mixture was heated to ca. 60°C until two clear layers were formed. The water layer was removed and treated again with  
5 degassed 30% aq. NaOH (200 mL), then washed with degassed H<sub>2</sub>O (300 mL x 2), brine (200 mL), dried over Na<sub>2</sub>SO<sub>4</sub>, filtered and evaporated. The residue was treated with degassed EtOH at 80°C for 5 min, then cooled to 0°C and filtered. The residue was washed with degassed EtOH and dried *in vacuo* to give the desired product (42.3 g, 97%).

10

$(\alpha)_D^{23} = +42.5$ , (c=1.0, CHCl<sub>3</sub>)

<sup>1</sup>H NMR (CDCl<sub>3</sub>): δ 7.21-7.12 (m, 18H), 7.03-6.95 (m, 4H), 6.70-6.65 (m, 4H), 3.08 (s, 6H);

<sup>31</sup>P NMR (CDCl<sub>3</sub>): δ -14.2;

15 <sup>13</sup>C NMR(CDCl<sub>3</sub>): δ 157.5-127.8 (m, Ar-C), 110.7, 54.7.

*(R)*-(6,6'-Dihydroxybiphenyl-2,2'-diyl) bis(diphenylphosphine) ((R)-HO-BIPHEP):

20 A solution of (*S*)-(6,6'-dimethoxybiphenyl-2,2'-diyl)bis(diphenylphosphine) ((*R*)-MeO-BIPHEP) (23.3g, 40 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (500 mL) was cooled to -78 °C and purged with N<sub>2</sub> for 15 min, BBr<sub>3</sub> (30.0g, 120 mmol) was added via a syringe over a period of 10 min. The solution was stirred at -78 °C for 1 h, and was warmed slowly to room temperature overnight. Then the mixture was cooled to 0  
25 °C and degassed water (120 mL) was added slowly until two clear layers were formed. The aqueous layer was removed and the organic layer was washed subsequently with degassed H<sub>2</sub>O (200 mL x 2), brine (200 mL) and dried over Na<sub>2</sub>SO<sub>4</sub>. The organic layer was passed through a pad of neutral Al<sub>2</sub>O<sub>3</sub> and evaporated to dryness, the solid thus obtained was essentially pure and directly  
30 used for the next step.

$(\alpha)_D^{23} = -10.4$ , ( $c=0.5$ , EtOH)

$^1\text{H}$  NMR ( $\text{CD}_2\text{Cl}_2$ ):  $\delta$  7.3-6.8 (m, 26H), 4.27 (s, br, 2H);

$^{31}\text{P}$  NMR ( $\text{CD}_2\text{Cl}_2$ ):  $\delta$  -13.6;

$^{13}\text{C}$  NMR( $\text{CD}_2\text{Cl}_2$ ):  $\delta$  154.9-116.7 (m, Ar-C).

5 HRMS: 555.1649, Calcd. for ( $\text{M}^+ + 1$ ): 555.1643.

General Procedure for (R)-(6,6'-Alkylene-2,2'-diyl) bis(diphenylphosphine) ((R)-(CH<sub>2</sub>)<sub>n</sub>-TunaPhos):

10 A solution of (R)-(6,6'-Dihydroxybiphenyl-2,2'-diyl) bis(diphenylphosphine) ((R)-HO-BIPHEP) (1.11g, 2 mmol) in DMF (20 mL) was purged with N<sub>2</sub> for 15 Min., anhydrous K<sub>2</sub>CO<sub>3</sub> (1.38 g, 10 mmol) was added as a solid and stirred at room temperature for 15 min. Bromochloromethane (2.1 mmol) was added via a syringe and stirred at room temperature for 24 h, then  
15 heated to 60°C, stirred until the starting material was completely consumed (~ 48 h). The solvent was removed under vacuum and the residue was extracted with ether (100 mL), washed with water (20 mLx2), brine (20 mL) and dried over Na<sub>2</sub>SO<sub>4</sub>. After removal of the solvent, the foamy solid was purified by flash chromatography on a silica gel with CH<sub>2</sub>Cl<sub>2</sub>-hexanes (1:3) as eluent. C3, C4, C5,  
20 C6-TunaPhos could be made using this procedure. For the synthesis of C2 TunaPhos, up to 3.5 eq. of 1,2-dibromoethane was used to make a complete conversion of the starting material.

25 C1-TunaPhos (1)

$(\alpha)_D^{23} = -396$ , ( $c=0.5$ , CHCl<sub>3</sub>);

$^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  7.8-7.0 (m, 26H), 5.41 (s, 2H);

$^{31}\text{P}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  -9.7;

30  $^{13}\text{C}$  NMR( $\text{CDCl}_3$ ):  $\delta$  152.9-121.0 (m, Ar-C), 101.6;

HRMS: 567.1672, Calcd. for ( $M^+$ +1): 567.1643.

C2-TunaPhos (2)

5

$(\alpha)_D^{23} = -294$ , ( $c=0.5$ ,  $\text{CHCl}_3$ );

$^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  7.8-7.0 (m, 26H), 4.30 (d, 2H,  $J=8.7$  Hz), 4.00 (d, 2H,  $J=8.7$  Hz);

$^{31}\text{P}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  -8.4;

10  $^{13}\text{C}$  NMR( $\text{CDCl}_3$ ):  $\delta$  159.8-122.4 (m, Ar-C), 74.3;

HRMS: 581.1816, Calcd. for ( $M^+$ +1): 581.1799.

C3-TunaPhos (3)

15

$(\alpha)_D^{23} = -225$ , ( $c = 0.5$ ,  $\text{CHCl}_3$ );

$^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  7.5-6.7 (m, 26H), 4.1-4.0 (m, 4H), 1.68(t,  $J = 5.7$  Hz, 2H);

$^{31}\text{P}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  -11.7;

$^{13}\text{C}$  NMR( $\text{CDCl}_3$ ):  $\delta$  157.8-118.8 (m, Ar-C), 72.2, 29.6;

20 HRMS: 595.1922, Calcd. for ( $M^+$ +1): 595.1956.

C4-TunaPhos (4)

25  $(\alpha)_D^{23} = -167$ , ( $c = 0.5$ ,  $\text{CHCl}_3$ );

$^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  7.6-6.7 (m, 26H), 4.19(d,  $J = 11.5$  Hz, 2H), 3.77(d,  $J = 10.4$  Hz, 2H), 1.68(t,  $J = 10.4$  Hz, 2H), 1.55(d,  $J = 11.5$  Hz, 2H);

$^{31}\text{P}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  -11.2;

$^{13}\text{C}$  NMR( $\text{CDCl}_3$ ):  $\delta$  156.3-115.5(m, Ar-C), 69.7, 25.5;

30 HRMS: 609.2100, Calcd. for ( $M^+$ +1): 609.2112.

C5-TunaPhos (5)

- 5  $(\alpha)_D^{23} = -143$ , ( $c = 0.5$ ,  $\text{CHCl}_3$ );  
 $^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  7.6-6.9 (m, 26H), 4.3-4.2 (m, 2H), 4.0-3.8 (m, 2H), 1.9-1.4 (m, 6H);  
 $^{31}\text{P}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  -11.4;  
 $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  157.0-113.5 (m, Ar-C), 67.2, 26.0, 22.3;  
 10 HRMS: 623.2261, Calcd. For ( $\text{M}^+ + 1$ ): 623.2269.

C6-TunaPhos (6)

- 15  $(\alpha)_D^{23} = -122$ , ( $c = 0.5$ ,  $\text{CHCl}_3$ );  
 $^1\text{H}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  7.8-6.8 (m, 26H), 4.1-4.0 (m, 2H), 3.7-3.6 (m, 2H), 1.9-1.4 (m, 8H);  
 $^{31}\text{P}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  -11.5;  
 $^{13}\text{C}$  NMR ( $\text{CDCl}_3$ ):  $\delta$  156.5-111.4 (m, Ar-C), 66.4, 25.9, 24.5;  
 20 HRMS: 637.2413, Calcd. for ( $\text{M}^+ + 1$ ): 637.2425.

EXAMPLE 225 Asymmetric Hydrogenation

- To a 10 mL Schlenk tube was added  $(\text{Ru}(\text{benzene})\text{Cl}_2)_2$  (10 mg, 0.02 mmol) and diphosphine (0.048 mmol of *R*-BINAP, *R*-MeOPHEP or C1-C6 TunaPhos) and then the tube was purged with  $\text{N}_2$  three times. Freshly distilled and  
 30 degassed DMF (1 mL) was added to this tube. The resulting mixture was heated

at 99-101 °C for 10 min., then cooled to 50 °C and the solvent was removed under vacuum. An orange to dark red solid was obtained, this solid was used directly as the catalyst. The catalyst was taken into a glove box and dissolved in degassed methanol (8 mL) and distributed equally to 8 vials (5 mL each). The  $\beta$ -ketoester  
5 was added, the mixture was sealed in a bomb and taken out of the glove box. The bomb was purged three times with H<sub>2</sub>, then the pressure was set to 750 psi. The reactor was set in an oil bath at 60 °C and was stirred for 20 h. The bomb was then cooled with an ice-bath, and H<sub>2</sub> was carefully released. The methanol solution was transferred to a 25 mL pear-shaped flask. After the removal of methanol,  
10 ether (20 mL) was added and the solution was washed with H<sub>2</sub>O (3 x mL), brine (3 mL), and dried over Na<sub>2</sub>SO<sub>4</sub>. The ether solution was passed through a short silica-gel column and concentrated to dryness before analysis.

15

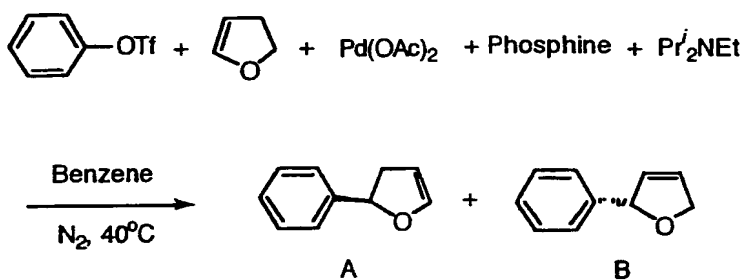
### EXAMPLE 3

#### Asymmetric Heck Reaction

Asymmetric Heck reaction is an attractive C-C bond forming reaction. A  
20 typical Pd-catalyzed Heck reaction was carried out with BINAP, MeO-BIPHEP and TunaPhos ligands, the results are outlined in Table 2.

With the TunaPhos ligands possessing an even number of methylene groups give better ee's than TunaPhos ligands with an odd number of methylene groups.  
25 Accordingly, in the standard asymmetric Heck reaction (phenyl triflate and 2,3-dihydrofuran as substrates), using C1-TunaPhos as ligand, 69.7%ee was obtained while 90.5%ee was obtained with C6-TunaPhos.

30

Table 2. Heck Reaction: Ligand Effect<sup>a</sup>

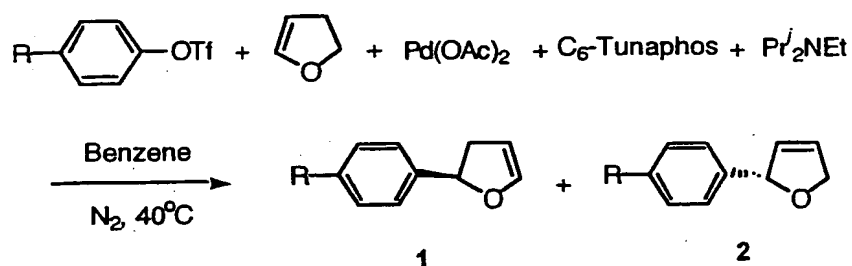
Phosphine <sup>b</sup>	A:B	A (ee%)	B (ee%)
Binap	95:5	79.0	61.5
MeO-Phep	94:6	88.8	31.5
C1-Tunaphos	94:6	69.7	10.8
C2-Tunaphos	98:2	78.4	35.7
C3-Tunaphos	95:5	72.6	24.5
C4-Tunaphos	96:4	88.8	62.8
C5-Tunaphos	91:9	75.2	24.1
C6-Tunaphos	95:5	90.5	61.6

<sup>a</sup>All of the reactions were run with a ratio of PhOTf:2,3-dihydrofuran: Pr<sub>2</sub>NEt: Pd(OAc)<sub>2</sub>: Phosphine=1:5:3:0.03:0.063, in 2 ml of benzene for 40h; <sup>b</sup> R-phosphines were used.



Under these conditions, C6-TunaPhos was used as the ligand to test  
5 various substrates. The results are summarized in Table 3.

Table 3 Asymmetric Heck reaction with C6-TunaPhos



R	yield	1 : 2	1 (ee%)	2 (ee%)
CF <sub>3</sub>	91%	92:8	96.3	47.5
NO <sub>2</sub>	93%	91:9	95.8	42.0
CN	88%	92:8	91.2	60.2
Cl	90%	90:10	93.2	59.6
CH <sub>3</sub>	a	97:3	91.4	n/a
Br	a	84:16	93.3	0
OTf		82:18	92.0	34.0

a Low conversion (~20%)

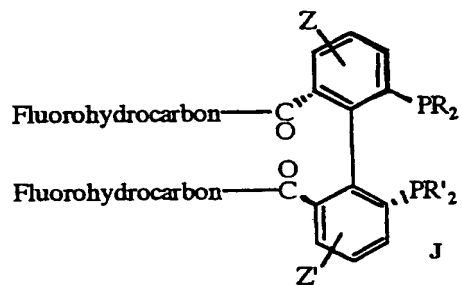
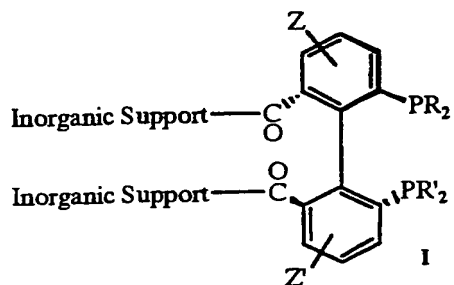
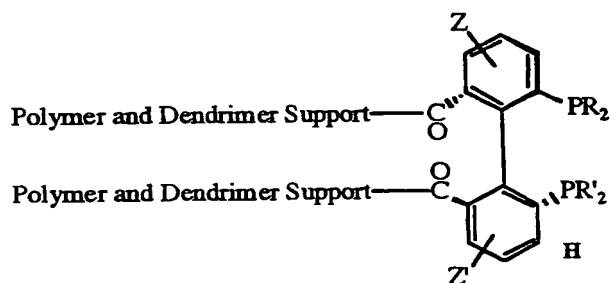
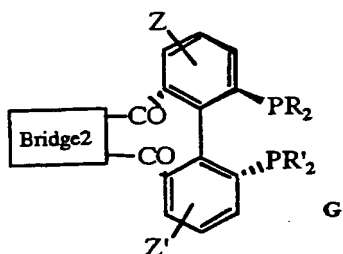
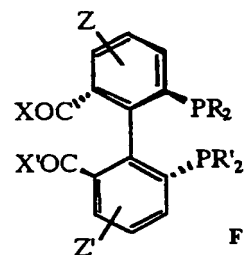
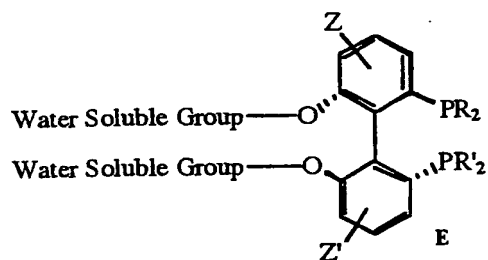
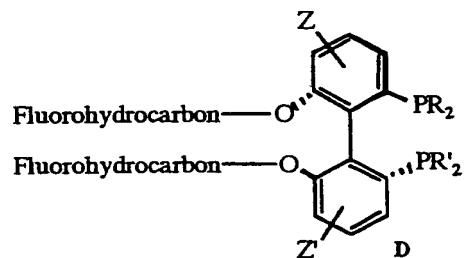
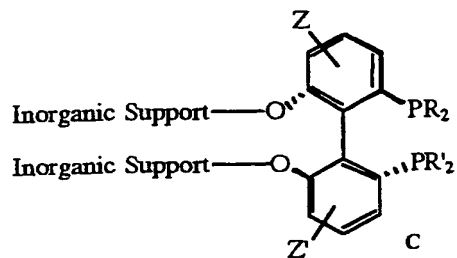
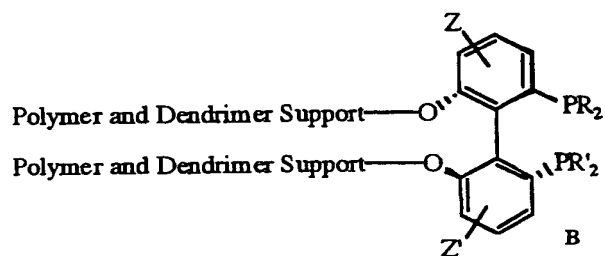
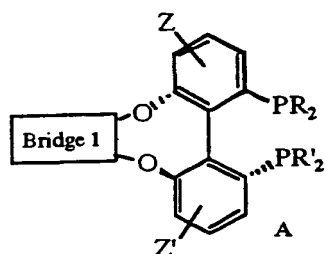
Alternative work-up and isolation procedures are also possible, and will be evident to those skilled in the art.

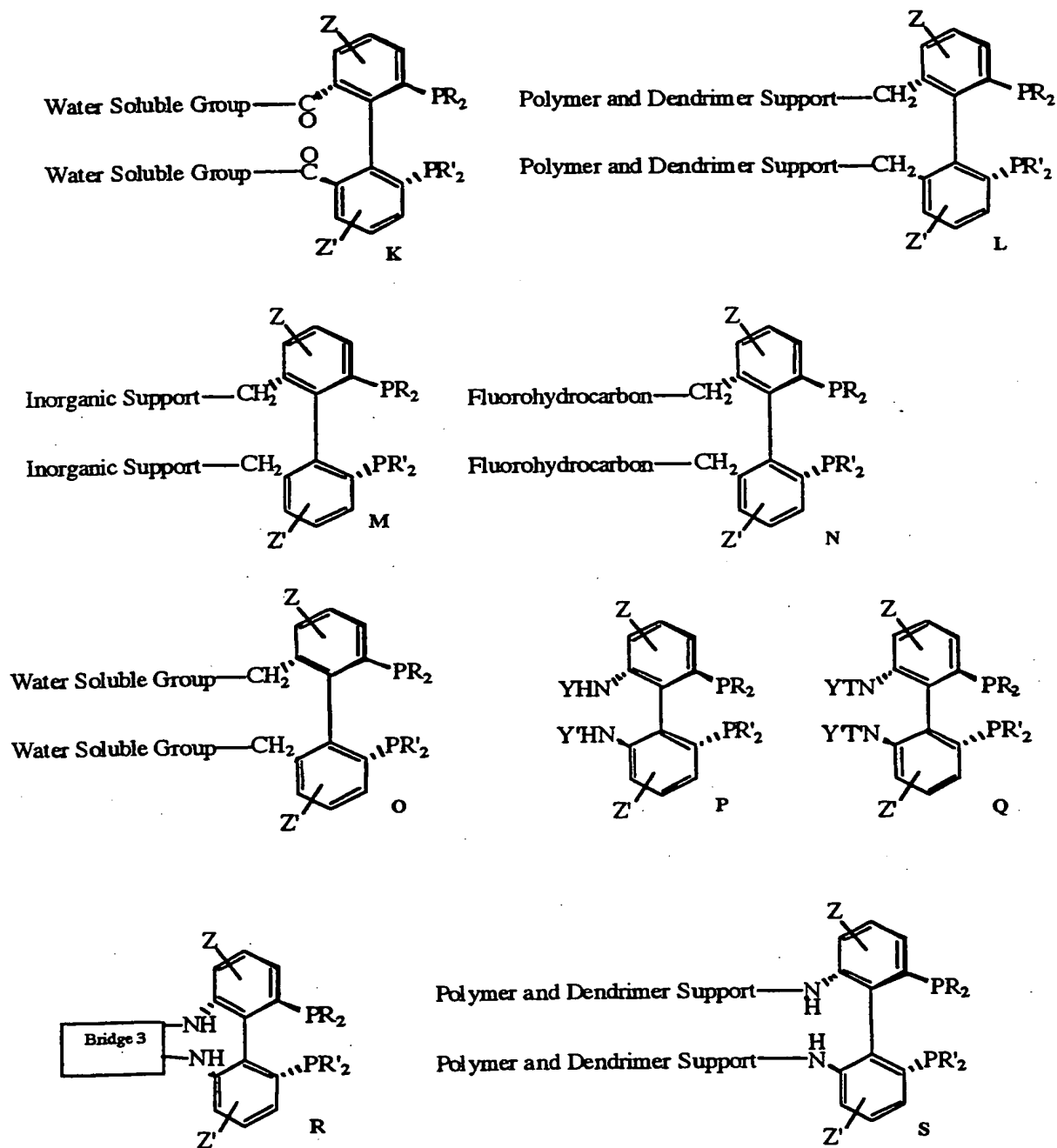
5           The present invention has been described with particular reference to the preferred embodiments. It should be understood that the foregoing descriptions and examples are only illustrative of the invention. Various alternatives and modifications thereof can be devised by those skilled in the art without departing from the spirit and scope of the present invention. Accordingly, the present  
10 invention is intended to embrace all such alternatives, modifications, and variations that fall within the scope of the appended claims.

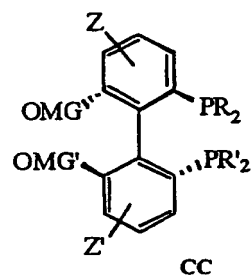
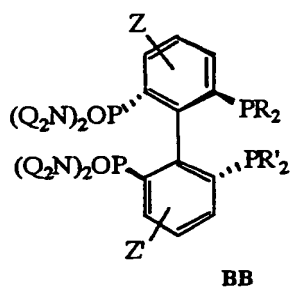
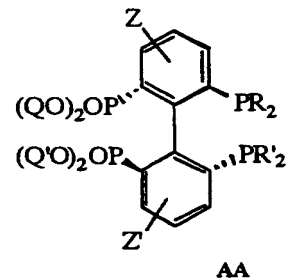
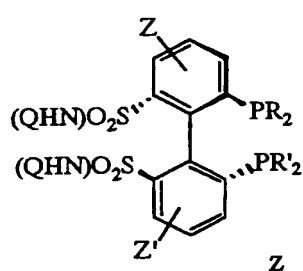
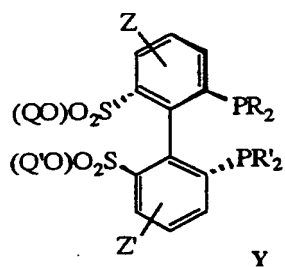
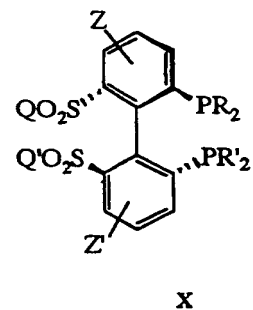
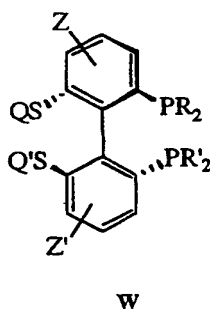
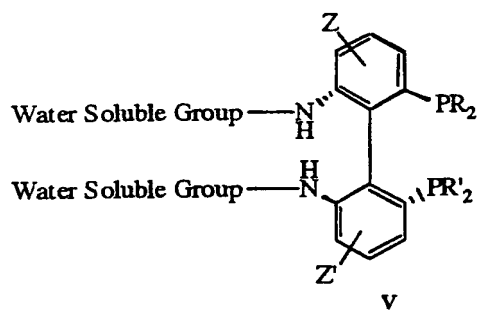
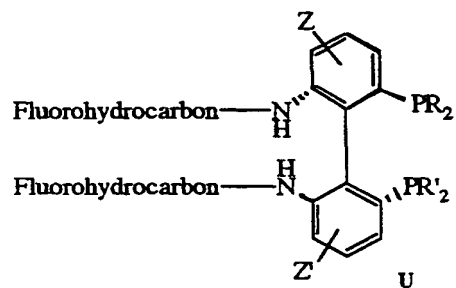
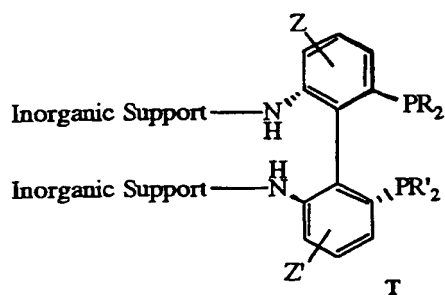
**WHAT IS CLAIMED IS:**

1. A ligand selected from the group consisting of compounds represented by A through Z, AA, BB and CC:

5







wherein "bridge 1" is selected from the group consisting of: C=O, C=S, SO<sub>2</sub>, PO(OR<sup>1</sup>), PO(NHR<sup>1</sup>), PO(NR<sup>1</sup>R<sup>2</sup>), divalent phenyl, substituted divalent phenyl, 2,2'-divalent-1,1'-biphenyl, substituted 2,2'-divalent-1,1'-biphenyl, 2,2'-divalent-1,1'-binaphthyl, substituted 2,2'-divalent-1,1'-binaphthyl, 1,1'-ferrocene, substituted 1,1'-ferrocene, SiR<sup>1</sup><sub>2</sub> (CH<sub>2</sub>)<sub>n</sub> where n is an integer ranging from 1 to 8, and (CR<sup>2</sup>)<sub>n</sub>X<sup>1</sup>(CR<sup>2</sup>)<sub>m</sub> wherein each n, m is independently an integer from 1 to 8, wherein X<sup>1</sup> is selected from the group consisting of: O, S, NR<sup>3</sup>, PR<sup>3</sup><sub>2</sub>, <sup>+</sup>NR<sup>3</sup><sub>2</sub>, <sup>+</sup>PR<sup>3</sup><sub>2</sub>, divalent aryl, divalent fused aryl, divalent 5-membered ring heterocyclic group and divalent fused heterocyclic group;

wherein "bridge 2" is selected from the group consisting of: NH, O, a single bond, (CH<sub>2</sub>)<sub>n</sub>, O(CH<sub>2</sub>)<sub>n</sub>O, NH(CH<sub>2</sub>)<sub>n</sub>NH, wherein each n is independently an integer from 1 to 8, divalent phenyl, substituted divalent phenyl, divalent phenyl amine, substituted divalent phenyl amine, 2,2'-divalent-1,1'-biphenyl, substituted 2,2'-divalent-1,1'-biphenyl, 2,2'-divalent-1,1'-binaphthyl, substituted 2,2'-divalent-1,1'-binaphthyl, 1,1'-ferrocene, substituted 1,1'-ferrocene, O(CR<sup>2</sup>)<sub>n</sub>X<sup>1</sup>(CR<sup>2</sup>)<sub>m</sub>O, NH(CR<sup>2</sup>)<sub>n</sub>X<sup>1</sup>(CR<sup>2</sup>)<sub>m</sub>NH and (CR<sup>2</sup>)<sub>n</sub>X<sup>1</sup>(CR<sup>2</sup>)<sub>m</sub> wherein each n, m is independently an integer from 1 to 8, wherein X<sup>1</sup> is selected from the group consisting of: O, S, NR<sup>3</sup>, PR<sup>3</sup><sub>2</sub>, <sup>+</sup>NR<sup>3</sup><sub>2</sub>, <sup>+</sup>PR<sup>3</sup><sub>2</sub>, divalent aryl, divalent fused aryl, divalent 5-membered ring heterocyclic group and divalent fused heterocyclic group;

wherein "bridge 3" is selected from the group consisting of: SO<sub>2</sub>, CO, COCO, OC(CH<sub>2</sub>)<sub>n</sub>CO, (CH<sub>2</sub>)<sub>n</sub> wherein n is an integer ranging from 1 to 8, COArCO, wherein Ar is selected from the group consisting of: divalent phenyl, substituted divalent phenyl, 2,2'-divalent-1,1'-biphenyl, substituted 2,2'-divalent-1,1'-biphenyl, 2,2'-divalent-1,1'-binaphthyl, substituted 2,2'-divalent-1,1'-binaphthyl, 1,1'-ferrocene, substituted 1,1'-ferrocene and CO(CR<sup>2</sup>)<sub>n</sub>X<sup>1</sup>(CR<sup>2</sup>)<sub>m</sub>CO wherein each n, m is independently an integer from 1 to 8, wherein X<sup>1</sup> is selected from the group consisting of: O, S, NR<sup>3</sup>, PR<sup>3</sup><sub>2</sub>, <sup>+</sup>NR<sup>3</sup><sub>2</sub>, <sup>+</sup>PR<sup>3</sup><sub>2</sub>, divalent aryl, divalent fused aryl, divalent 5-membered ring heterocyclic group and divalent fused heterocyclic group;

wherein each  $R^1$  is independently selected from the group consisting of: aryl, alkyl, alkaryl, aralkyl and substituted derivatives thereof wherein the substituent in said substituted derivatives is selected from the group consisting of: carboxylic acid, alkoxy, hydroxy, alkylthio, thiol and dialkylamino;

5            wherein each  $R^2$  and  $R^3$  is independently selected from the group consisting of: aryl, alkyl, substituted aryl and substituted alkyl group;

             wherein each said substituted divalent phenyl, divalent phenyl amine, biphenyl, binaphthyl and ferrocene derivative comprises at least one substituent selected from the group consisting of aryl, substituted aryl, alkyl, heteroatom, F,  
10    Cl, Br, I,  $\text{COOR}^1$ ,  $\text{SO}_3\text{R}^1$ ,  $\text{PO}_3\text{R}^1_2$ ,  $\text{OR}^1$ ,  $\text{SR}^1$ ,  $\text{PR}^1_2$ ,  $\text{AsR}^1_2$ ,  $\text{SbR}^1_2$ , OAr, nitro, amino, vinyl, substituted vinyl and sulfonic acid;

             wherein each R and R' is independently selected from the group consisting of: aryl, alkyl, alkaryl, aralkyl and substituted derivatives thereof, wherein the substituent in said substituted derivatives is selected from the group consisting of:  
15    carboxylic acid, alkoxy, hydroxy, alkylthio, thiol, dialkyl amino groups;

             wherein each X and X' is independently selected from the group consisting of: aryl, alkyl, alkaryl, aralkyl, alkoxy, alkoxy, hydroxy, alkylthio, thiol, primary amine, secondary amine and  $\text{ArNH}$ ;

             wherein each Z and Z' is independently selected from the group consisting of: halogen, alkyl, aryl, aryloxy, nitro, amino, vinyl, substituted vinyl and sulfonic acid; and  
20

             wherein each Q, Q', Y, Y', T and T' is independently selected from the group consisting of: aryl, alkyl, alkaryl, aralkyl and substituted derivatives thereof, wherein the substituent in said substituted derivatives is selected from the group  
25    consisting of: carboxylic acid, alkoxy, hydroxy, alkylthio, thiol and dialkylamino.

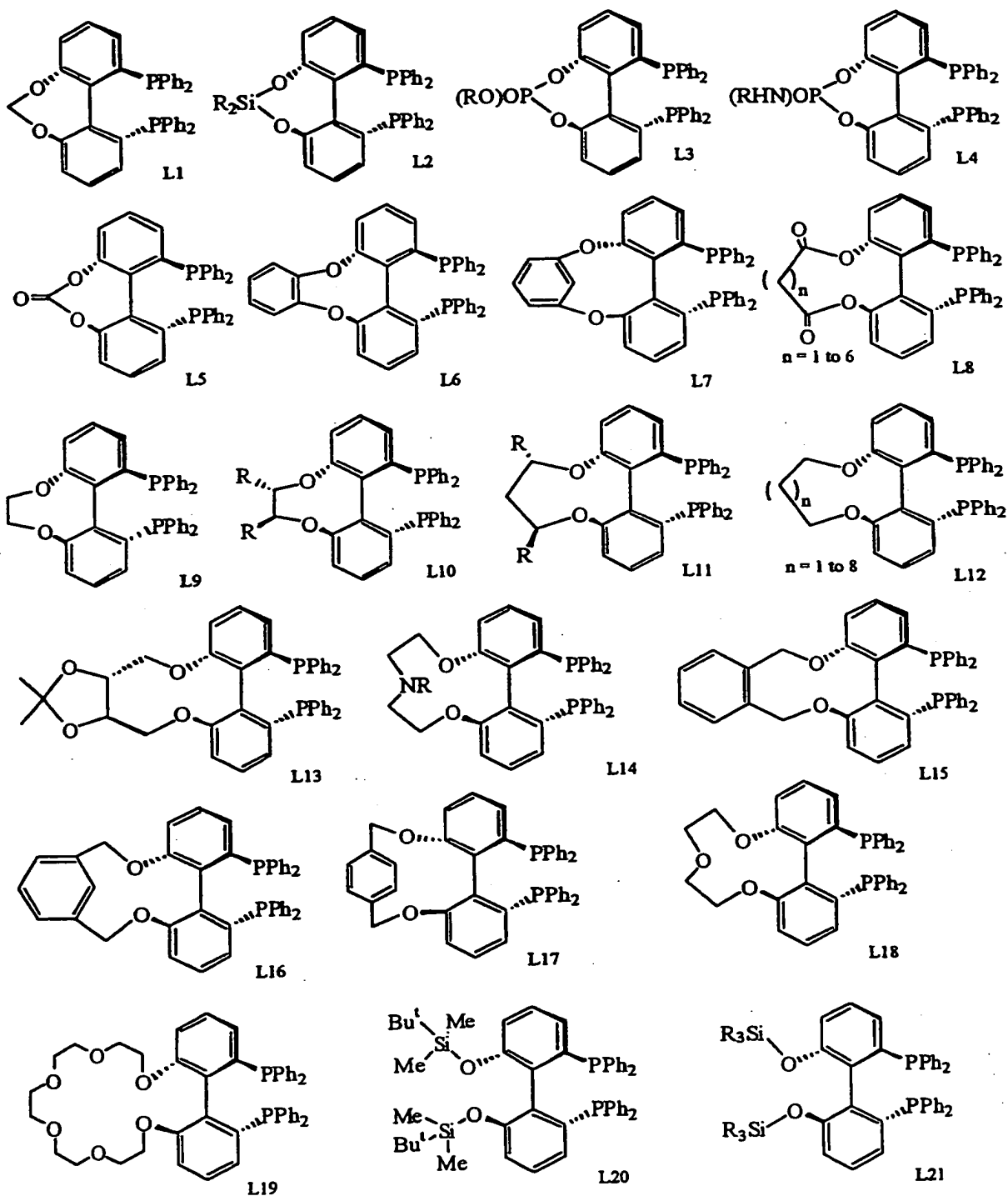
2.        The ligand of claim 1, wherein said ligand is a racemic mixture of enantiomers.

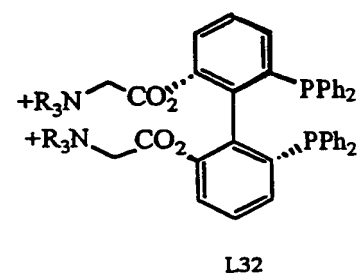
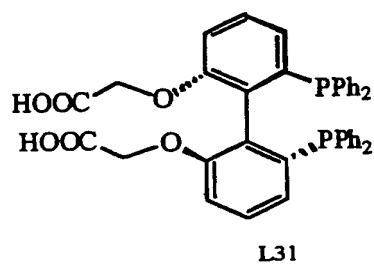
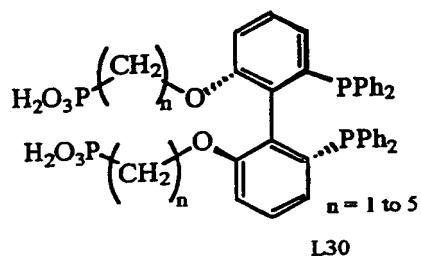
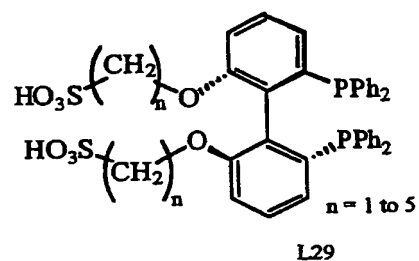
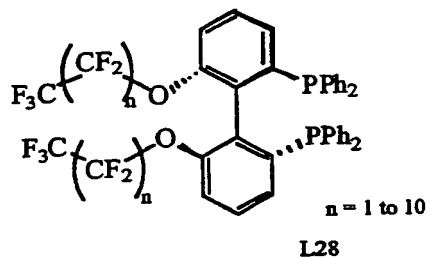
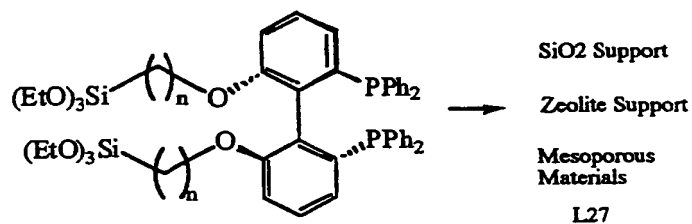
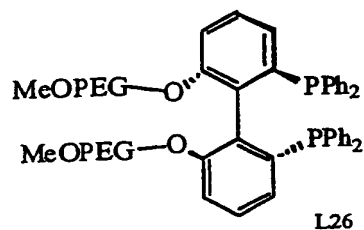
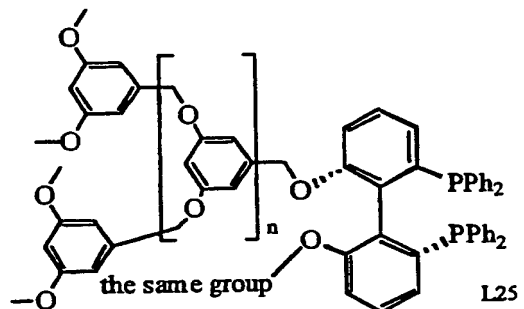
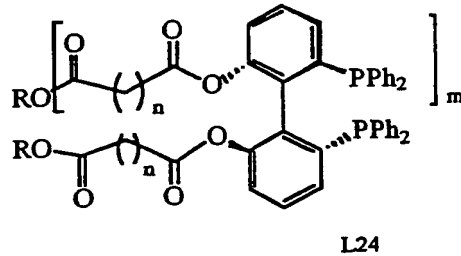
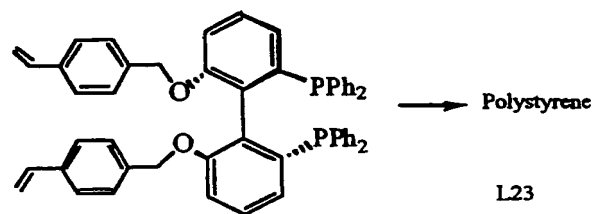
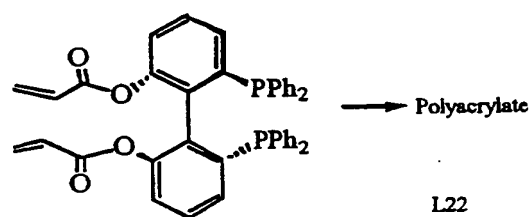
30        3.        The ligand of claim 1, wherein said ligand is a non-racemic mixture of enantiomers.

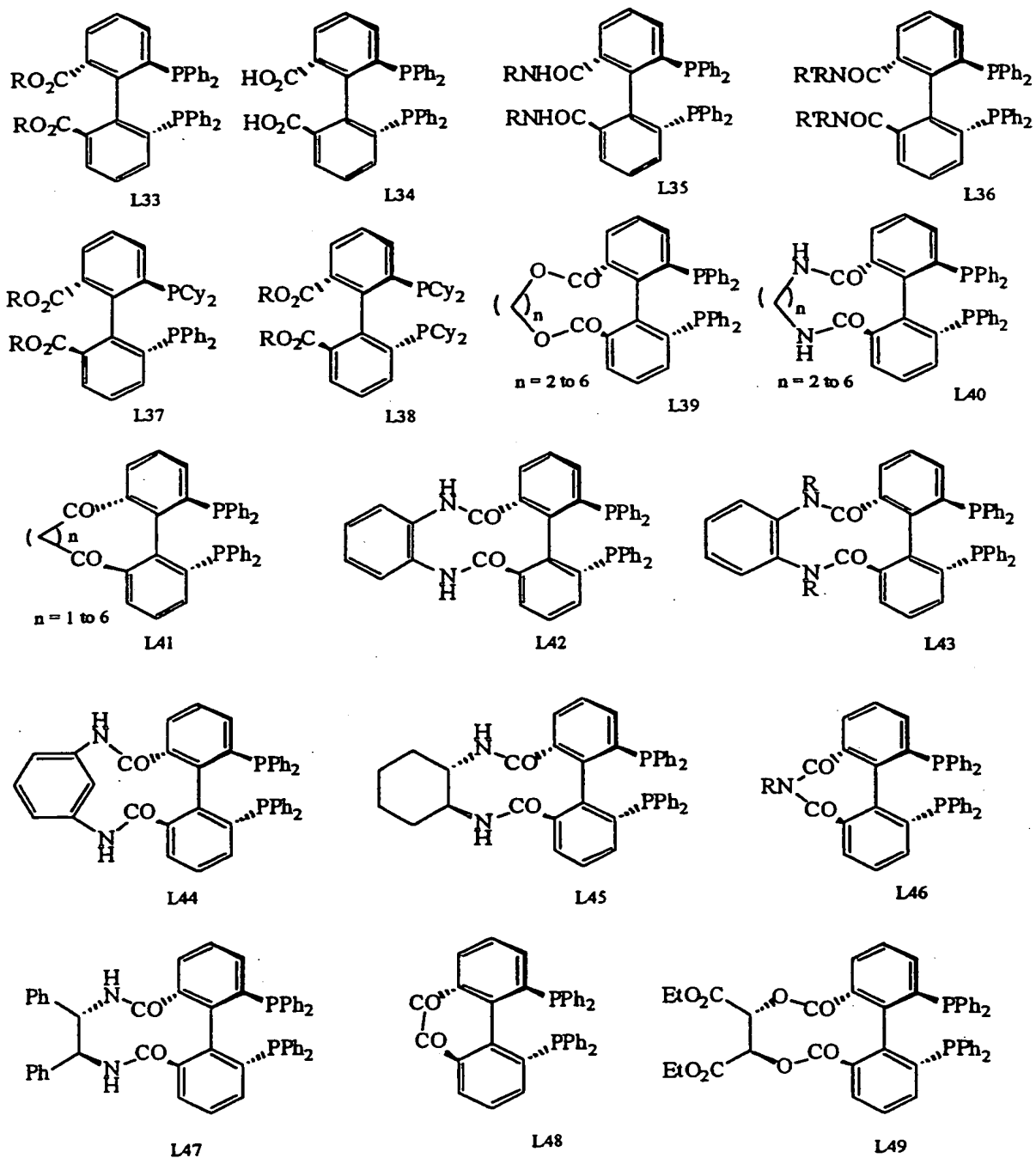


4. The ligand of claim 1, wherein said ligand is one of the enantiomers.
5. The ligand of claim 1, having an optical purity of at least 85% ee.
- 5 6. The ligand of claim 1, having an optical purity of at least 95% ee.
7. The ligand of claim 1, wherein said ligand is in a polymeric or  
copolymeric form.
- 10 8. The ligand of claim 1, wherein said ligand is supported on a support  
material.
9. The ligand of claim 8, wherein said support is a polymer support.
- 15 10. The ligand of claim 9, wherein said polymer support is selected  
from the group consisting of polystyrene, polyacrylate, resin, PEG, MeO-PEG,  
dendritic polyester and dendritic polyenamide.
- 20 11. The ligand of claim 8, wherein said support is an inorganic support.
12. The ligand of claim 11, wherein said inorganic support is a  
mesoporous material.
- 25 13. The ligand of claim 11, wherein said inorganic support is selected  
from the group consisting of: silica, alumina, zeolite and molecular sieve.
14. The ligand of claim 8, wherein said ligand is linked to a support  
material by a linker group.
- 30

15. The ligand of claim 8, wherein said linker is selected from the group consisting of:  $\text{NH}(\text{CH}_2)_n\text{Si}(\text{OEt})_3$ ,  $\text{CO}(\text{CH}_2)_n\text{Si}(\text{OEt})_3$ ,  $(\text{CH}_2)_n\text{Si}(\text{OEt})_3$ , C-O, C-N and  $\text{NCF}_2$  linker, wherein  $n = 1$  to 8.
- 5 16. The ligand of claim 1, including at least one water soluble functional group.
17. The ligand of claim 1, wherein said water-soluble functional group is selected from the group consisting of: sulfuric, phosphoric, carboxylic, 10 quaternary ammonium and MeO-PEG.
18. A ligand selected from the group consisting of:





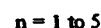




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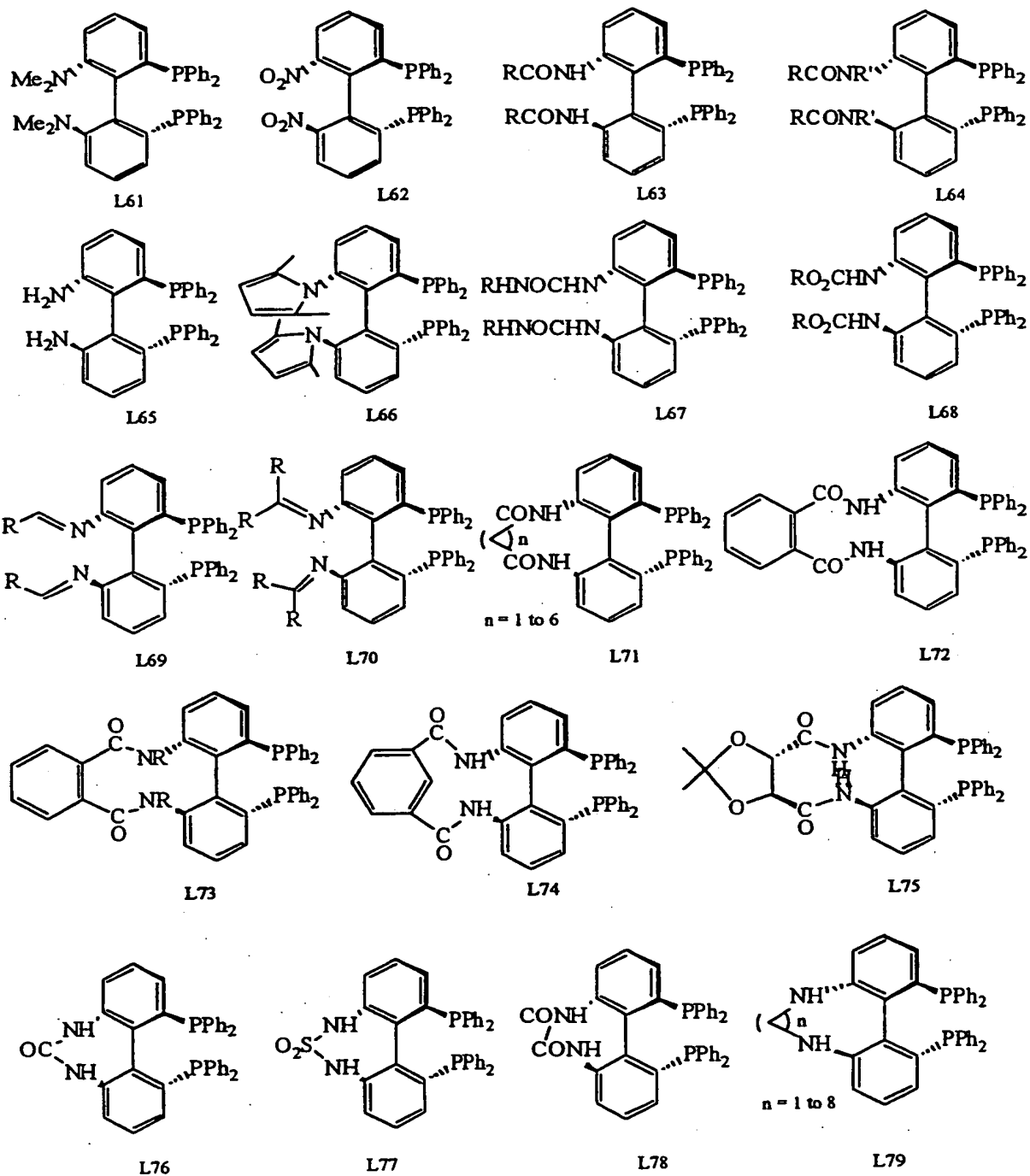
**L56**

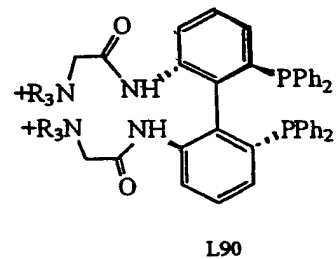
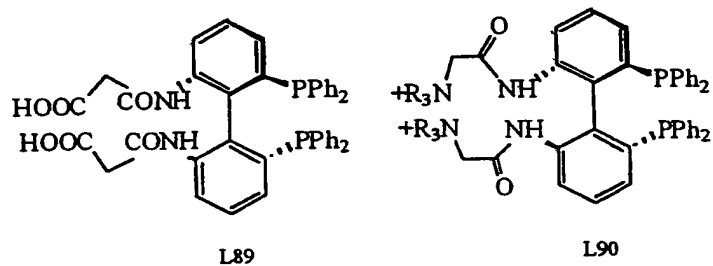
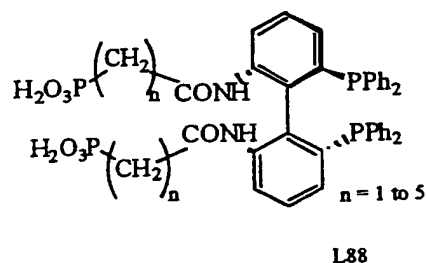
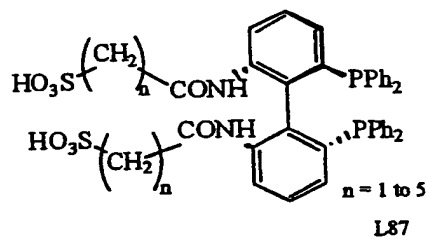
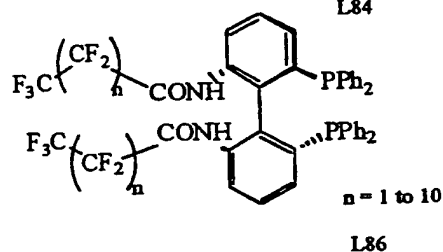
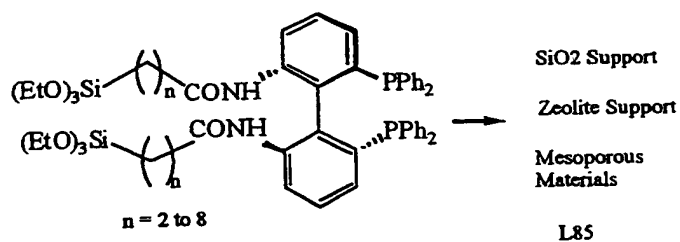
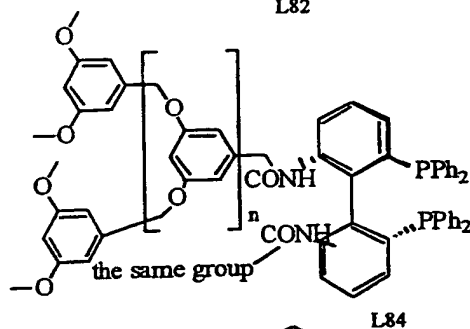
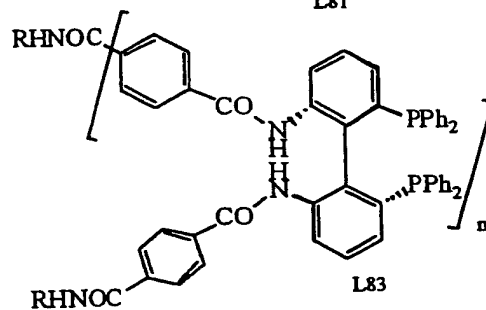
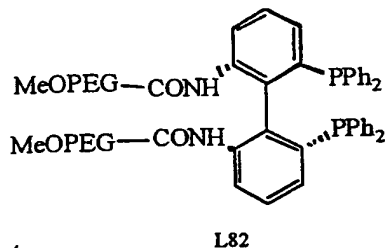
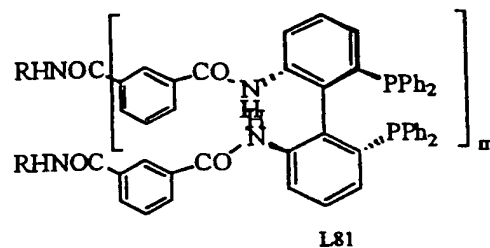
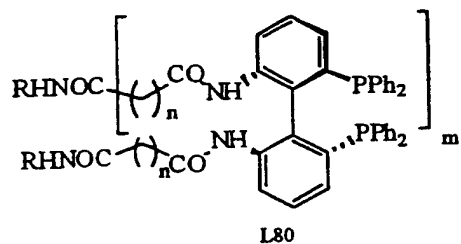


LS7

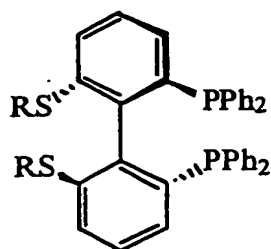


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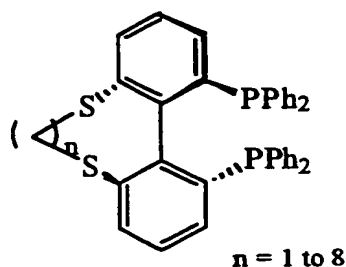






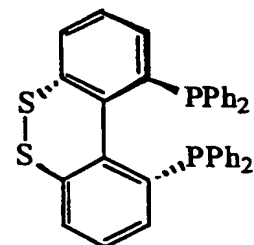


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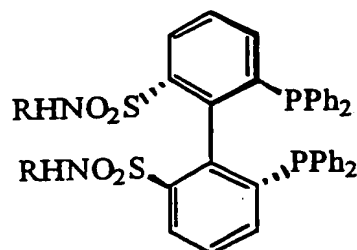


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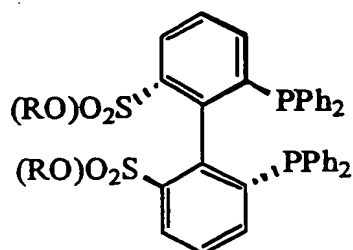
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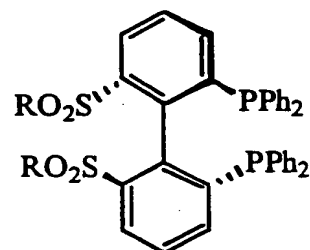
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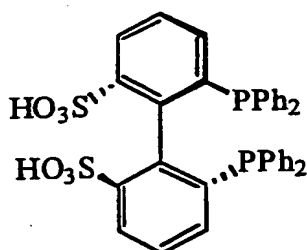
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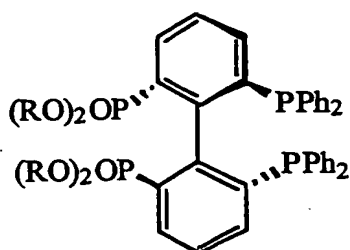
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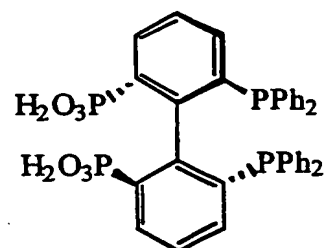
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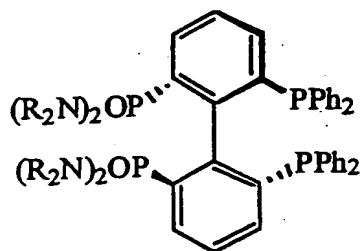
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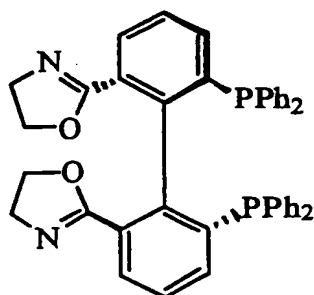
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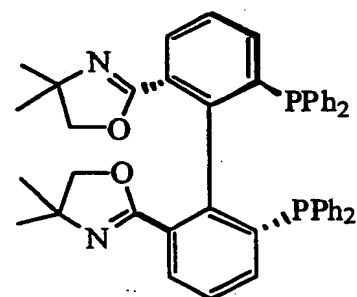
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19. A catalyst prepared by a process comprising: contacting a transition metal salt, or a complex thereof, and a ligand according to claim 1.

20. The catalyst of claim 19, wherein said catalyst is a racemic mixture of enantiomers.

21. The catalyst of claim 19, wherein said catalyst is a non-racemic mixture of enantiomers.

22. The catalyst of claim 19, wherein said catalyst is one of the enantiomers.

23. The catalyst of claim 19, having an optical purity of at least 95% ee.

24. The catalyst of claim 19, wherein said transition metal is selected from the group consisting of: Pt, Pd, Rh, Ru, Ir, Cu, Ni, Mo, Ti, V, Re and Mn.

25. The catalyst of claim 19, wherein said transition metal is selected from the group consisting of: Pd, Rh, Ru and Ir.

20

26. The catalyst of claim 24, wherein said transition metal salt, or complex thereof, is selected from the group consisting of:  $\text{PtCl}_2$ ;  $\text{Pd}_2(\text{DBA})_3$ ;  $\text{Pd}(\text{OAc})_2$ ;  $\text{PdCl}_2(\text{RCN})_2$ ;  $(\text{Pd}(\text{allyl})\text{Cl})_2$ ;  $(\text{Rh}(\text{COD})\text{Cl})_2$ ;  $(\text{Rh}(\text{COD})_2)\text{X}$ ;  $\text{Rh}(\text{acac})(\text{CO})_2$ ;  $\text{Rh}(\text{ethylene})_2(\text{acac})$ ;  $\text{Rh}(\text{CO})_2\text{Cl}_2$ ;  $\text{Ru}(\text{RCOO})_2(\text{diphosphine})$ ;  $\text{Ru}(\text{methylallyl})_2(\text{diphosphine})$ ;  $\text{Ru}(\text{aryl group})\text{X}_2(\text{diphosphine})$ ;  $\text{RuCl}_2(\text{COD})$ ;  $(\text{Rh}(\text{COD})_2)\text{X}$ ;  $\text{RuX}_2(\text{diphosphine})$ ;  $\text{RuCl}_2(=\text{CHR})(\text{PR}'_3)_2$ ;  $\text{Ru}(\text{ArH})\text{Cl}_2$ ;  $\text{Ru}(\text{COD})(\text{methylallyl})_2$ ;  $(\text{Ir}(\text{COD})_2\text{Cl})_2$ ;  $(\text{Ir}(\text{COD})_2)\text{X}$ ;  $\text{Cu}(\text{OTf})$ ;  $\text{Cu}(\text{OTf})_2$ ;  $\text{Cu}(\text{Ar})\text{X}$ ;  $\text{CuX}$ ;  $\text{NiX}_2$ ;  $\text{Ni}(\text{COD})_2$ ;  $\text{MoO}_2(\text{acac})_2$ ;  $\text{Ti}(\text{OiPr})_4$ ;  $\text{VO}(\text{acac})_2$ ;  $\text{MeReO}_3$ ;  $\text{MnX}_2$  and  $\text{Mn}(\text{acac})_2$ ; wherein each R and R' is independently selected from the group consisting of: alkyl or aryl; Ar is an aryl group; and X is a counteranion.

25

30

27. The catalyst of claim 26, wherein said counteranion X is selected from the group consisting of: halogen,  $\text{BF}_4$ ,  $\text{B}(\text{Ar})_4$  wherein Ar is 3,5-di-trifluoromethyl-1-phenyl,  $\text{ClO}_4$ ,  $\text{SbF}_6$ ,  $\text{CF}_3\text{SO}_3$ ,  $\text{RCOO}$  and a mixture thereof.

5 28. The catalyst of claim 19, prepared in situ or as an isolated compound.

29. A process for preparation of an asymmetric compound comprising:  
contacting a substrate capable of forming an asymmetric product by an  
10 asymmetric reaction and a catalyst prepared by a process comprising: contacting a transition metal salt, or a complex thereof, and a ligand according to claim 1.

30. The process of claim 29, wherein said asymmetric reaction is selected from the group consisting of: hydrogenation, hydride transfer,  
15 hydrosilylation, hydroboration, hydrovinylation, hydroformylation, hydrocarboxylation, isomerization, allylic alkylation, cyclopropanation, Diels-Alder reaction, Heck reaction, isomerization, Aldol reaction, Michael addition and epoxidation.

20 31. The process of claim 30, wherein said asymmetric reaction is hydrogenation; and said substrate is selected from the group consisting of: ethylenically unsaturated compound, imine, ketone, enamine, enamide and vinyl ester.

25 32. The process of claim 31, wherein said catalyst is an Ru complex of a chiral ligand selected from the group consisting of: C1-TunaPhos, C2-TunaPhos, C3-TunaPhos, C4-TunaPhos, C5-TunaPhos and C6-TunaPhos, and said asymmetric reaction is hydrogenation of ketones to produce a chiral alcohol.

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US00/25635

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : C07F 9/02, 9/52, 15/00; B01J 31/00

US CL : 568/17; 556/18, 502/162

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 568/17; 556/18, 502/162, 171; 252/182.3, 182.31; 260/665r, dig.25

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched  
NONEElectronic data base consulted during the international search (name of data base and, where practicable, search terms used)  
WEST USPAT

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,847,222 A (YOKOZAWA et al.) 08 December 1998, see the abstract, examples, and claims.	1-32
Y	US 5,621,128 A (JENDRALLA) 15 April 1997, see the abstract, examples, and claims.	1-32
Y	US 5,907,045 A (ANTOGNAZZA et al.) 25 May 1999, see the abstract, examples, and claims.	1-32
Y	US 5,880,301 A (SHIBASAKI et al.) 09 March 1999, see the abstract, examples, and claims.	1-32

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents	* T* Later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
* A* document defining the general state of the art which is not considered to be of particular relevance	* N* document of particular relevance, the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
* E* earlier document published on or after the international filing date	* V* document of particular relevance, the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
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* O* document referring to an oral disclosure, use, exhibition or other means	
* P* document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

14 DECEMBER 2000

Date of mailing of the international search report

16 JAN 2001

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